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Studies of geological properties and conditions for deep disposal of radioactive waste, Denmark. Phase 1, report no. 10

Characterization and evaluation of geological properties and conditions at 500 meters depth

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DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

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Preface

The present report is a contribution to a major project whose purpose is to investigate whether suitable geological sites for disposal of the Danish radioactive waste can be identified. The Geological Survey of Denmark and Greenland (GEUS) has been given the task of identifying, mapping, and characterizing laterally continuous, low permeability rock formations occurring at 500 meters depth with thicknesses of 100 meters. This report is part of a series of ten reports presenting the results of the first phase of the siting project, which has mainly been carried out as a desk study.

The initial geological characterization and evaluation will provide the geological basis for the selection of two sites where detailed geological site investigations will be carried out in the project's second phase. These two sites will be selected through a dialogue process between the Ministry of Higher Education and Science (MHES) and the local municipalities. The geological data from the site investigations will be used as input to a safety case once a disposal concept has been identified by the Danish Decommissioning (DD). The safety case must demonstrate that the geological properties in combination with the engineered barriers of the repository can provide the required short- and long-term safety for disposal.

In a preceding feasibility study, it was concluded that at 500 meters depth potential host rocks occur in Jurassic and Lower Cretaceous claystones, in Upper Cretaceous carbonates, and in Precambrian crystalline basement rocks. In the current project phase, the geological properties and subsurface conditions related to these stratigraphic intervals and rock types are reviewed based on existing data. The potential host rocks' capabilities to retard radionuclides are investigated initially by conceptual 1D numerical modeling. In addition, natural processes potentially influencing short- and long-term subsurface stability are identified and described.

To enable characterization and a qualitative evaluation of the Danish subsurface at depths to 500 meters Denmark has been divided into eleven geological areas based on the information gathered in the geological reports no. 2–8. Each area is characterized by the type of potential host rock occurring at 500 meters depth, the rock types forming barriers in the overlying effective containment zone, and the structural framework. The evaluation is based on requirements and criteria for deep geological disposal, which are defined based on international experience and recommendations from similar projects. Based on the available data, each area is characterized and evaluated with regards to whether the geological properties and conditions are suitable for deep disposal of Danish radioactive waste. The results of the project's first phase are presented in the following ten geological reports:

1. Requirements and criteria for initial evaluation of geological properties and conditions
2. Geological setting and structural framework of Danish onshore areas
3. Upper Cretaceous – Paleocene chalk, limestone and marl distribution and properties
4. Jurassic and Lower Cretaceous claystone distribution, sedimentology, and properties
5. Precambrian crystalline basement distribution and properties
6. Subsurface distribution of Jurassic and Cretaceous fine-grained formations based on seismic mapping
7. Evaluation of long-term stability related to glaciations, climate and sea level, groundwater, and earthquakes
8. Conceptual 1D modeling of nuclide transport in low permeable formations
9. Karakterisering og evaluering af geologiske egenskaber og forhold i 500 meters dybde (In Danish)
10. Characterization and evaluation of geological properties and conditions at 500 meters depth (This report is an English translation of report no. 9)

This report is Report no. 10. It presents the basis for a subdivision into 11 geological areas and an initial qualitative evaluation of whether the rock properties and subsurface conditions in each area fulfil the requirements and criteria for deep geological disposal.

Content

Appendix A
Detailed area evaluation

Appendix B
Blechschmidt, I., Frieg, B., Vomvoris, s., Turner, J. and Tweed, C., 2021: Geological siting project on deep disposal of the Danish radioactive waste. Review of Phase 1, report no. 8. Criteria and requirements for identification of suitable sites. (The reviewed report is the present report no. 1).

0. Introduction to the report

This report presents an evaluation of the Danish subsurface with the purpose of identifying areas where the geological properties and conditions at depths around 500 meters are favourable for the potential establishment of a deep repository for Danish radioactive waste. The evaluation, which is summarized in Chapter 7 of this report, is based on the characterization and mapping of the Danish subsurface at depths to 500 meters below ground level. The detailed mapping and characterization are presented in seven geological reports prepared as part of the siting project (Reports no.2–8, cf. references in Chapter 8.1). Criteria for geological properties and conditions that are required to provide effective geological barriers and stable geological conditions are defined and described in Report No. 1 (cf. references in Chapter 8.1). The criteria are defined based on the requirements given in Danish Parliament's decision B90 (Danish Parliament, 2018) and recommendations from similar international projects on deep geological disposal.

This introductory chapter briefly describes the content of this report.

Chapter 1 contains an introduction to the Danish disposal project and the international guidelines for deep geological disposal of radioactive waste. The geological siting project was initiated to investigate whether a suitable site for deep geological disposal of Danish radioactive waste at a depth around 500 meters below ground level can be identified. The geological siting project carried out by the Geological Survey of Denmark and Greenland (GEUS) comprises two main phases. The first phase is mainly based on a review and compilation of existing data. The results provide the geological basis for the selection of two sites for detailed geological investigations. The sites should be selected by means of a dialogue process between the Ministry of Higher Education and Research (MHES) and the municipalities. In the next project phase, detailed geological and geophysical surveys will be carried out at the two sites, including drilling of deep wells to more than 500 meters depth and acquisition of new seismic data. The detailed investigations will be carried out in order to evaluate whether the presence of favourable geological properties and conditions for deep disposal can be confirmed.

Chapter 2 presents the geological requirements and criteria that will be used to evaluate whether a site is potentially suitable for deep geological disposal of the radioactive waste. The criteria are defined based on international recommendations and experiences from similar projects, and the safety relevance of the criteria is summarised. At a geological disposal site, tight geological formations form passive barriers in the subsurface. Together with engineered barriers such as containers and backfill in the repository, the geological formations will ensure the retention and retardation of radioactive nuclides in the subsurface. The host rock is the geological formation in which a repository can potentially be established. In the overlying shallower section tight formations constitute effective barriers in the effective containment zone (referred to as ECZ). The criteria address the spatial distribution and homogeneity of the rocks, geochemical conditions, short- and long-term stability in the area, geotechnical properties, and the possibilities of identifying sites where representative and reliable new geological data can be collected.

Chapter 3 presents a summary of the existing knowledge of the geological properties of the Jurassic and Cretaceous claystones and carbonates and the Precambrian crystalline basement. Furthermore, a brief description is given of the younger Cenozoic sedimentary succession, which in this project is not regarded as part of the ECZ due to a high content of sand. A summary of the conceptual, numerical 1D modeling of nuclide transport in claystone and carbonate rock is also presented. The modeling shows that based on current knowledge, both claystones and carbonates can provide geological barriers that contribute to the retention and retardation of radioactive nuclides in the subsurface. One parameter that is seen to have a significant influence on nuclide transport is the hydraulic gradient, which is site specific.

Chapter 4 presents the subsurface distribution of the geological formations containing potential host rocks as mapped from seismic data and deep boreholes. The characteristic geological and structural architecture of the subsurface in different parts of the country is illustrated by representative geological cross-sections. Based on the structural framework and stratigraphic record at depths to 500 meters, Denmark is divided into 11 areas, each of which has a characteristic geological record and structural framework. The division into areas has been made to enable a characterization and evaluation of the geological properties and conditions of potential host rocks and barriers in each area, based on the defined criteria.

Chapter 5 presents the geological criteria and specific properties that are regarded as favourable for each criterion. The chapter describes the concept for the evaluation of whether favourable properties for the criteria are met. Specific properties of each criterion are assigned a sub-score, which forms the basis for the overall evaluation of the criterion. The evaluation of the criteria is qualitative and is scored using a colour scale with three levels. Green is used when reliable data show that predominantly favourable properties for the criterion are present in most of the area. Yellow is used when analogies or less reliable data indicate that favourable properties can generally be expected in most of the area. Orange is used when reliable data from the area shows that the properties are generally less favourable.

Chapter 6 presents an evaluation of each area based on the defined criteria. In some areas, where both claystone and carbonate sections occur at depths around 500 meters, an evaluation has been made for both types of potential host rocks. The chapter contains detailed thematic maps, lithological interpretation of petrophysical borehole logs and depth and thickness maps for all the mapped stratigraphic intervals. The maps and geological cross-sections presented in Chapter 4, and the properties of claystone, carbonate, and granite / gneiss basement (Chapter 3) form the basis for the criteria evaluation. The maps presented in Chapter 6 can be used in the process of selecting specific sites for geological investigations in the next project phase.

Chapter 7 presents a summary of the evaluations and general comments on the evaluations. Many criteria score green or yellow, meaning that favourable properties and conditions are present or are expected to be present in large areas. The frequent occurrence of yellow scores reflects the general lack of specific geological data from the Danish subsurface at depths to 500 meters. For all criteria that are scored less favourably (orange), there is a brief description of the specific geological properties which have resulted in this less favourable scoring, together with comments on the possible consequences and/or mitigations for radioactive waste disposal in this area.

Chapter 8 contains a list of the references in the report text. In addition, various reports and publications which have been prepared during previous geological surveys and studies related to the disposal of Danish radioactive waste in a near-surface to intermediate depth repository (Områdestudier and Mellemlager) are listed.

Appendix A contains the detailed criteria evaluations of the geological properties and comments on the properties and their sub-scores for all areas.

Appendix B contains a review report with comments and recommendations for the geological criteria defined by GEUS and the concept for evaluation of the areas. The report has been prepared by an international expert group (Blechschmidt et al. 2021).

1. Introduction

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

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

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

1.1 Guidelines for identification of repository sites

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

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

These recommendations in addition to experience from siting projects in other countries have been used to identify investigations that need to be performed in the Danish project.

Experience from other countries include France (ANDRA, 2005), Finland (POSIVA, 2017a, b), Netherlands (COVRA, 2018), Switzerland (SFOE, 2008; Nagra, 2017) and Sweden (SKB, 2007).

Numerous studies of the potential for deep geological disposal of radioactive waste have been carried out for several decades by countries where nuclear power contributes to the energy supply. The waste from nuclear power production comprises high level (heat generating) waste which is different from the Danish waste comprising mostly low-level waste and small volumes of special waste. The geological criteria for suitable sites for geological disposal are identified from these studies with the purpose to dispose large amounts of high-level waste. For the Danish siting project, a cautious approach is taken at this stage by applying similar criteria and similar methods for site investigations. This ensures that all necessary and potentially relevant properties and conditions are addressed during the geological characterization and evaluation carried out in the siting project's first phase. The site-specific geological properties and conditions required for safe disposal of the Danish radioactive waste will depend on the waste inventory and the disposal concept and design, which have not yet been identified. A review of the geological criteria as defined in Report no.1 (c.f. reference in Chapter 8) was carried out by a team of international experts from Switzerland and UK. Comments and recommendations from the review are presented in Blechschmidt et al. (2021) (Appendix B).

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

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

1.2 Concept for deep geological disposal of radioactive waste

The concept for deep geological disposal of radioactive consist of a system with three barriers encapsulating the waste as described below (IAEA, 2011):

1. Inner engineered barrier: This barrier is provided by a container of stainless steel, cupper or other resistant material containing the radioactive waste.
2. Intermediate barrier (engineered): Sealing material such as bentonite or cement surrounding the waste containers in the subsurface repository (borehole or cavern)
3. Outer passive geological barrier (low permeable rock): The outer barrier is low permeable rocks with high capability for retention and retardation of radioactive nuclides in the subsurface. The rock where the waste is disposed is referred to as the host rock and the overlying low permeable layers forming additional barriers towards flow constitute the effective containment zone (ECZ).

The engineered barriers are designed to ensure longest possible sealing and retention of radioactive nuclides. Over time chemical reactions between groundwater and the waste containers will result in corrosion and a gradual degradation of the inner barrier. The intermediate engineered barrier will together with the host rock and overlying barriers ensure the retardation and retention of eventually leaked radioactive nuclides in the deep subsurface thus preventing transport into shallower levels and the biosphere.

Identification of a safe and feasible disposal concept for the Danish radioactive waste requires an iterative process as it depends on the combined functionality of the geological and geotechnical properties of both the host rock and rocks in the ECZ, and the engineered barriers. The geological conditions in a specific area will impact the geotechnical stability during the construction of a repository as well as during the disposal operation and subsequent closure. In case it is decided to dispose only the long-lived fraction of the Danish waste in a deep repository and dispose the LLW at shallower depths specific criteria for shallow disposal need be defined and applied for the site selection and evaluation.

The next phase of this siting project (phase 2) comprises detailed geological investigations of two sites where comprehensive data acquisition programs will provide new data on the geological, geochemical, and geotechnical properties of the host rock and rocks in the ECZ. This data will be used to evaluate the barrier effectiveness of the rocks and to investigate the geochemical interaction between the radioactive nuclides and the geochemical conditions of the groundwater. This information can be used as part of the iterative process to develop the optimum design of the engineered barriers to ensure long-term retardation of radioactive nuclides.

A specific concept design for a deep geological repository has not yet been defined by DD but several concepts have been identified (Dansk Dekommissionering, 2021). The potential concepts range from a deep borehole for disposal of the long-lived waste only combined with a shallow repository, to a large underground construction for disposal of all the waste at 500 meters depth. The geological criteria in the present siting project have been defined with the purpose to ensure the sites may be suitable for deep disposal of all the waste in case this concept is preferred for disposal. This approach ensures that areas where favourable properties and conditions are identified will be favourable for deep disposal of both large and smaller volumes of waste.

Prior to a decision on whether to dispose the radioactive waste in a deep repository at a specific site a safety evaluation of the functionality of the combined system of engineered and geological barriers has to be made. The safety case must demonstrate that the repository can provide the necessary safety and retardation of radioactive nuclides in both the short and long term (IAEA, 2011).

1.3 The geological siting project

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

The first phase of the present geological siting project comprises a geological review of all data available in the GEUS archives, from stored drill-samples, and from literature. The data have been used to map and describe relevant properties of the potential host rocks identified, and the natural processes potentially influencing their short- and long-term geological stability. The results form the basis of a subdivision into eleven geologically different areas which are characterized and evaluated regarding the areas' potential suitability for deep disposal of the Danish radioactive waste as described in the present Report No. 10 (cf. Chapter 7.1 for reference).

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

Geological data from the Danish onshore area is scattered and of varying quality. Archives and databases comprise 2D seismic data of different vintages and quality as they have been acquired for varying purposes. Well data exist mainly from deep wells drilled for hydrocarbon exploration, some geothermal wells, and other technical/scientific drillings. As the data from different regions of Denmark varies in vintage, quality and level of detail, the current picture is by no means comprehensive. However, the geological desk studies combined with some new sedimentological and stratigraphic studies, and initial sensitivity studies from conceptual 1D modeling, have proven highly valuable for identification of major data gaps and critical parameters, where the acquisition of new data during the next project phase is important.

As part of the detailed investigations in the next phase of the project, new data and information will be collected at the two sites. The extensive data collection program will include drill-cores, well logs, and groundwater samples - thus, providing samples and measurements for laboratory analyses and various other studies. Based on the new data, a characterization and evaluation of the geological suitability for radioactive waste disposal at the two sites will be made. This characterization will also be used by DD in an iterative process to identify a suitable repository design, and for the evaluation of the combined retention capacity of the engineered and the geological barriers as input to a safety case.

2. Geological requirements and criteria

The purpose of the geological studies in the present project is, as described in The Danish Parliament's resolution B90 *"… to investigate whether it will be possible to identify geologically suitable sites for a deep repository (at greater depth than previous intermediate storage studies)"* (Danish Parliament, 2018).

The geological requirements stipulated in decision B90 for a potential disposal site are that a final repository should be placed at a depth of around 500 meters, in a low-permeability host rock that has a thickness of 100 meters and is horizontally extensive for several kilometers. The rock must be sufficiently homogeneous both lithologically and mineralogically, and it must be without significant discontinuities such as larger fractures and faults. Finally, the general geological conditions in the area must be stable in both the short and long term (Danish Parliament, 2018). The two main phases of the geological siting project are illustrated in Figure 2.1 (green boxes).

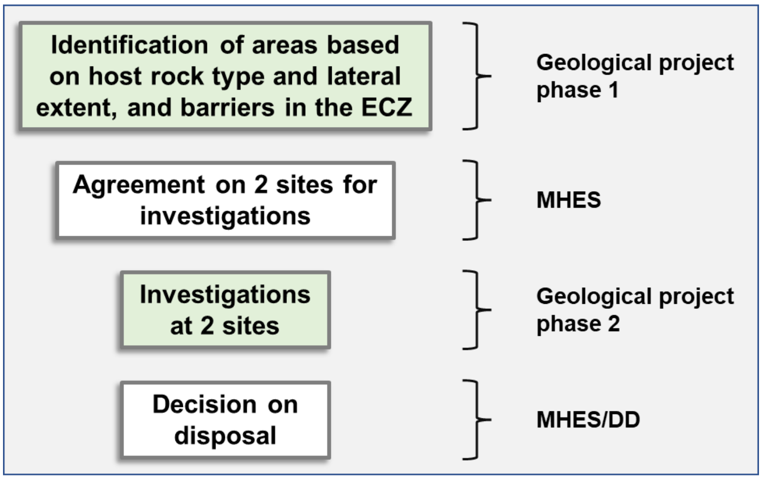


Figure 2.1. *The geological disposal project comprises two major phases. The current phase 1 is finalised by the conclusions presented in this report. In the following phase 2 detailed geological site investigations will be carried out in two areas prior to an eventual decision on deep geological disposal of the radioactive waste.*

2.1 Host rock properties and geological conditions

Specific geological criteria are defined in order to evaluate barrier effectiveness of potential host rocks and the geological stability in different parts of Denmark. The geological criteria are based on the requirements in B90 (Danish Parliament, 2018) and recommendations and experience from international geological disposal projects. A systematic evaluation of the defined criteria ensures that all relevant geological properties and conditions are initially investigated and described to provide the best possible basis for selection of investigations sites. New data from the site investigations will be analysed and evaluated prior to making a decision on whether a deep geological repository can be established.

2.2 Criteria for geological properties and conditions

The geological criteria are presented and described in detail in Report No. 1 (cf. references in Chapter 8.1). The criteria as listed in Table 2.1 are defined to ensure that all relevant aspects of the geological properties and conditions in the subsurface that may affect the safety of a deep geological radioactive waste repository in the short and long term are assessed. The systematic evaluation of the criteria also helps to identify data and knowledge gaps where new data needs to be acquired during the detailed geological site investigations in phase 2.

Table 2.1. *Overview of criteria groups and criteria.*

Criteria Group	Criteria
1. Properties of the host rock and the containment zone	1.1 Spatial extent
	1.2 Hydraulic barrier effectiveness
	1.3 Geochemical conditions for retardation
	1.4 Release pathways
2. Long-term natural stability	2.1 Stability of the site and rock properties
	2.2 Erosion
	2.3 Repository induced influences
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions
	3.2 Underground access and drainage
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock
	4.2 Explorability of spatial conditions
	4.3 Predictability of long-term changes

The extent to which the criteria and related geological parameters are regarded as being favourable depends on both the disposal concept and the nature and volume of the waste. A preliminary identification of possible disposal concepts is presented by Danish Decommissioning (2021). Safe disposal in the subsurface depends on the combined effect of the geological and the engineered barriers in the repository. Some of the geological criteria may be more important to meet than others, but at the current stage it is not possible to rank them all as they depend on the disposal concept and the final repository design, which are not yet defined. All the criteria and the related geological properties and conditions are defined to ensure that effective barriers and stable geological conditions in both the short and long term will prevent radioactive material from being transported into the groundwater zone and the biosphere.

It should be noted that the criteria are largely defined based on recommendations from international projects on disposal of large inventories of high-level radioactive waste containing heat-generating material which is not present in the Danish waste. This means that some of the defined criteria may be of less importance for safe disposal of the Danish waste comprising low to intermediate level waste.

2.3 Reasoning for division into geological areas

The purpose of dividing Denmark into geologically different areas is to evaluate the extent of favourable geological properties and conditions in each area. It is not intended to identify the optimal area and site. This is not possible due to many different, often unknown, parameters and their interactions with the designed barriers. The evaluation contributes to the identification of areas where favourable geological properties can be expected to be confirmed by the detailed geological investigations in the next project phase. The division into geological areas and their evaluation have been carried out in a stepwise process, as illustrated in Figure 2.2, and described in detail in Report no. 1 (cf. references in Chapter 8.1).

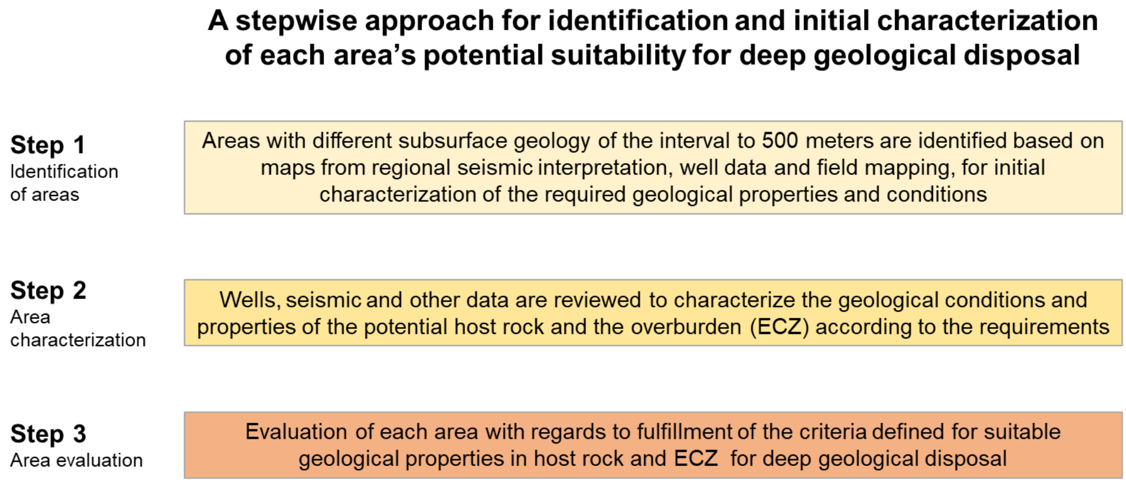


Figure 2.2. *Illustration of the stepwise process for division into geological areas and subsequent characterization and evaluation.*

The division into areas with a specific geological signature and structural framework will also provide the basis for identifying one (or more) disposal concepts that are suitable for the local geological conditions and properties.

Based on geological mapping and characterization of the subsurface (Reports 2–8, cf. references in Chapter 8.1), the Danish onshore area has been divided into 11 areas. This subdivision is relevant only for the present geological siting project. Each area is characterized by a dominant type of potential host rock at depths around 500 meters. The host rocks are claystones in the Jurassic and Lower Cretaceous intervals, carbonates in the Upper Cretaceous (Chalk Group) and granite / gneiss in basement rock. In addition to the potential host rock, the structural framework is also taken into consideration regarding the area division, as the occurrence of many faults within short distances has a significant impact on horizontal continuity.

In large areas of the Danish subsurface, carbonates occur in the ECZ, as illustrated conceptually in Figure 2.3. The uppermost Cenozoic section consists of alternating layers of sand and clay that vary in thickness often over short distances. In some areas, Cenozoic deposits are found down to depths of 400–500 meters or more, and in these cases, due to the high content of sand, no effective barrier rock has been demonstrated in the ECZ. In the area with basement rock, granite / gneiss constitutes both the host rock and the barriers in the ECZ.

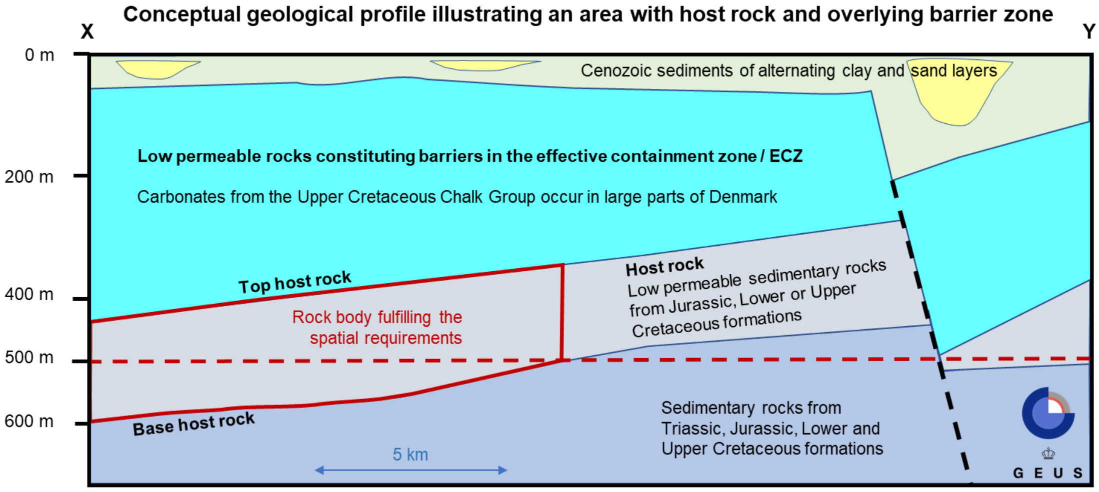


Figure 2.3. *The figure illustrates a conceptual geological succession with a host rock at depths around 500 meters and a carbonate interval constituting the barrier in the overlying effective containment zone (ECZ). A large fault offsetting the geological succession downwards is present on the right side of the cross-section. The presence of a rock body where the required depth and thickness is fulfilled is outlined by a red polygon. The 500 meters depth is shown with a dotted red line.*

For the criteria evaluation it is assumed that the ECZ extends upwards to a depth of approx. 140 meters below ground level, which is an estimated average depth for groundwater interests used in the conceptual numerical modeling (Report No. 8, cf. references in Chapter 8.1). Assuming that a repository is placed in a host rock occurring in the depth range from 400 to 500 meters, the distance to the average base of groundwater interests is thus 260 meters. For the definition of the required thickness of the barrier zone, an approximation of a thickness of about 250 meters is used, as the depth uncertainty for mapped formations can be tens of meters (Report no. 6, cf. references in Chapter 8.1). The required thickness of barrier rocks in the ECZ at a specific site will depend on the combined effect of the geological properties and hydrogeological conditions, and a thickness of 250 meters should be considered as indicative for this initial project phase.

3. Properties of the potential host rock and ECZ

Potential host rocks occurring in the Danish subsurface are claystones, carbonates, and crystalline basement. Claystone is found in Jurassic and Lower Cretaceous formations, carbonates (including chalk, limestone, and marl) constitute the Upper Cretaceous Chalk Group, and granite and gneiss are found in the Precambrian basement. The Jurassic and Lower Cretaceous formations also contain sandstones, which generally have high porosities and permeabilities. Sandstone does not contribute to geological barriers but can provide flow paths. The Cenozoic section comprises alternating layers of sand and clay of highly varying proportions and horizontal extension. Clay-rich intervals are found only locally at depths down to 500 meters and it is therefore considered that, in general, the Cenozoic formations do not contribute to barriers in the ECZ (c.f. reports listed in Chapter 8.1).

For a rock to act as a barrier it must be tight, i.e., have a very low permeability to fluids. Low permeability is a prerequisite for diffusion dominated transport of dissolved matter, which is very slow compared with transport controlled by fluid flow (advection). The geological properties that influence permeability are porosity, which is the volume of cavities between sediment grains, the lithological homogeneity, the amount of clay and the amount of clay minerals in the clay size fraction. The type of clay minerals is important because some clay minerals may contribute to the geochemical retention of nuclides in the subsurface. Additionally, some clay minerals promote self-healing of micro-fractures which may be generated in the rock during construction of the repository or by natural geological processes (e.g. fault movements). In addition to low permeabilities in the host rock and the ECZ, the hydrological gradient at a site has a significant impact on whether nuclide transport is controlled by diffusion, dispersion (dispersion of matter caused by the pore structure of the rock) or advective flow.

The geological/geomechanical properties of the rocks are important for the technical feasibility of the construction and the operation of the repository. Whether specific properties are favourable will depend on the disposal concept and facility design. For a large repository in the subsurface, the absence of layers or zones with significant flow of water will be of great importance for the feasibility and safety of construction work in the subsurface.

A very limited amount of data and analyses exist for specific geological parameters from the Danish subsurface at depths around 500 meters. A summary of the existing knowledge regarding the geological properties and their contribution to barrier effectiveness is presented in this chapter and is based on descriptions in Reports Nos. 2, 3, 4, 5 and 8 (cf. references in Chapter 8.1). Where available, representative data from each area are given in the area evaluation sections (Chapter 6).

The Cenozoic section, which in most areas occurs in the shallow successions above the ECZ is briefly described (Report no. 2, cf. reference in Chapter 8.1). Extensive descriptions of the uppermost 100-200 meters of the geological record can be found in reports from previous projects on radioactive waste disposal (cf. references in Chapter 8.2) and are not included in the present project, which focuses on depths around 500 meters.

Due to the limited data available regarding the geological properties at 500 meters depth, the barrier effectiveness of claystone and carbonate has been investigated initially by conceptual

1D modeling of nuclide transport (Report no. 2 cf. references in Chapter 8.1). To assess the host rock potential of claystone and carbonate the models examine the various parameter's influence on the barrier effectiveness in stochastic scenarios. The preliminary conclusion from these models is that with the current assumptions, both rock types can potentially be used as host rocks, and that the site-specific hydrological gradient will have a major impact on transport rates. A summary of the results is presented in Chapter 3.4.

Data

Information regarding the geological properties of potential host and barrier rocks is generally obtained from "hard" data based on analysis of cores from boreholes, and borehole logs. Drill cores provide the most detailed and accurate information about the lithology, bedding, and properties in the subsurface at the drilling site. Borehole logs show interpretations of various physical properties recorded by different measurement methods. Lithological variations in a formation on a scale close to, or less than the tools resolution (30–100 cm) can only be identified from drill cores. To obtain as reliable and accurate data as possible, it is important for the interpretation of borehole logs that they are calibrated to data from drill cores representing the different types of lithologies and properties in the logged interval. In cases where logs are not calibrated to core data, there will be a significant uncertainty regarding lithological interpretation, porosity, and permeability, which is important to acknowledge and quantify.

3.1 Clay, mineralogy, and barrier effectiveness

Clay is a common term for particles or minerals where the grain size is less than 2 µm. Clay minerals are layered silicates and other minerals that result in plasticity of the sediment. Clay hardens by drying and firing. Clay minerals that typically occur in the Danish subsurface at depths to 500 meters include kaolinite, smectite, mica and chlorite. A claystone is a rock type that consists of compacted sediment, dominated by clay-sized grains. Formations consisting predominantly of clay but including some coarser material, such as silt and sand, can also be referred to as claystones. In this report, the term claystone is used for a siliciclastic rock that contains large amounts (ideally> 50%) of particles in the clay fraction. Determination of the exact amount of clay particles in a sedimentary rock requires detailed analysis, and only limited data exist from analyses of the clay content in the Danish subsurface. The term claystone is often used based on a qualitative, visual estimate of the composition of the rock and it is also used on a larger scale for thicker clay-dominated units identified on well logs, which may contain thin layers of silt and / or sand.

The amount of clay in a sedimentary rock is an important parameter for assessing various rock properties. A high proportion of clay promotes a high degree of compaction during burial of the sediment and thus results in low porosity and permeability. By interpreting the clay content from petrophysical logs (typically a gamma log), the vertical homogeneity of a section can be assessed. Thus, clay layers having relatively small porosity and permeability compared to more coarse-grained layers can be identified. The homogeneity of a claystone is an important parameter as the presence of interbedded layers of well-sorted sediments with a larger grain size, will affect the rock's porosity and permeability and result in different horizontal and vertical permeability. The properties of claystone can vary significantly depending on frequency and thickness of interbedded, high porosity sand layers.

The presence of sand layers in a clay-dominated rock will also impact the geomechanical properties at various scales. Site specific data are required to assess the sand layers influence on the barrier effectiveness. The thickness and structural configuration of the layers and the gradient at the site must also be taken into consideration. Thus, to assess the barrier effectiveness of a claystone, it is therefore important to examine and characterize the amount of clay particles, the content of clay minerals, bedding thickness, and heterogeneity of the sediment.

Smectite represents a special group of clay minerals with the ability to bind large amounts of water resulting in a strong expansion capability, and contraction upon drying. Claystone with a high content of smectite has thus a high plasticity and high cohesion. This means that claystone comprising smectite has a great potential for self-healing of locally formed fractures. In addition, sediments with a high content of smectite will be exposed to a high degree of compaction compared to sediments with smaller amounts of smectite, and thus a lower permeability the higher the content of smectite. Smectite content can be determined by geochemical analysis of rock samples, but data exist from only a small number of samples from depths relevant to this siting project.

When the content of smectite is very high, the claystone can be described as plastic. The presence of plastic clay can be a technical challenge for boreholes and constructions in the subsurface, but if recognized in advance, potential problems can be mitigated. Local occurrences of plastic clay are well known from parts of the Cenozoic succession and from the Jurassic Fjerritslev Formation.

Calcite

Calcite crystals (of calcium carbonate) can be dissolved relatively easily at low pH values, transported in dissolved form and (re-)precipitated. Calcite is therefore often seen as fracture and pore cavity infill when rocks comprise high amounts of calcium carbonate. The ability to precipitate calcite can therefore be an important contribution to the self-healing properties of a sedimentary rock.

3.2 Jurassic and Lower Cretaceous claystone

The presence of claystone in the Danish subsurface is known from deep boreholes, where data has been collected as drill cores and petrophysical well logs. The formations dominated by claystones often contain sand layers of varying thickness and frequency, where the thickness of both clay layers and sand layers can vary from a centimeter scale to meters, or tens of meters (Figures 3.1 and 3.2). A summary of data from claystones from the Jurassic and Cretaceous formations is presented in Report no. 4 (cf. reference in Chapter 8.1).

__Figure 3.1.__ An outcrop example of a relatively homogeneous claystone (Lower Jurassic) exposed in a former clay pit near Gantofta in southern Sweden. The light streaks are thin laminae of silt and fine-grained sand within the clay-dominated section (Report no. 4).

__Figure 3.2.__ Core photo showing the interbedding of clay (dark) and sand (light) layers in the Jurassic Fjerritslev Formation, Stenlille-10 well. Each core is 1 meter long.

Porosity and permeability

Data from permeability measurements of Jurassic and Cretaceous claystone at 500 meters depths in the Danish subsurface is not available. In general terms, there is a correlation between porosity and permeability, and therefore data on the porosity of a rock is useful. A general correlation between porosity and burial depth can be assumed (Kristensen et al. 2016), but it is influenced by local conditions such as sediment composition, subsidence rate, uplift, and local diagenetic processes (recrystallisation and cementation after deposition). A recently deposited clay-dominated sediment has a porosity of 70% to 90%. During compaction, the porosity decreases rapidly to approximately 30% at depths around 1000 meters (Tucker, 2001). A parallel horizontal texture develops in the sediment during compaction which results in a measurable difference between vertical and horizontal permeability.

A slight decrease of permeability with depth is to some extent observed in the interval 1100–1900 meters from analysis of Fjerritslev Formation claystone (Lower Jurassic) however with a large spread of data points and based on a very small number of samples (Figure 3.3, from Olsen and Jørgensen, 2008).

Claystone and clay minerals

There are limited data on the content of clay-sized grains, clay minerals, and other minerals in the Jurassic and Cretaceous sediments, and the existing analyses show large variations both geographically and stratigraphically. Overall, only traces of calcite are reported from Jurassic clays whereas smectite generally is present in highly varying amounts. The Lower Cretaceous formations generally contain both smectite and calcite. In the following the clay content is reported as volume unless stated otherwise.

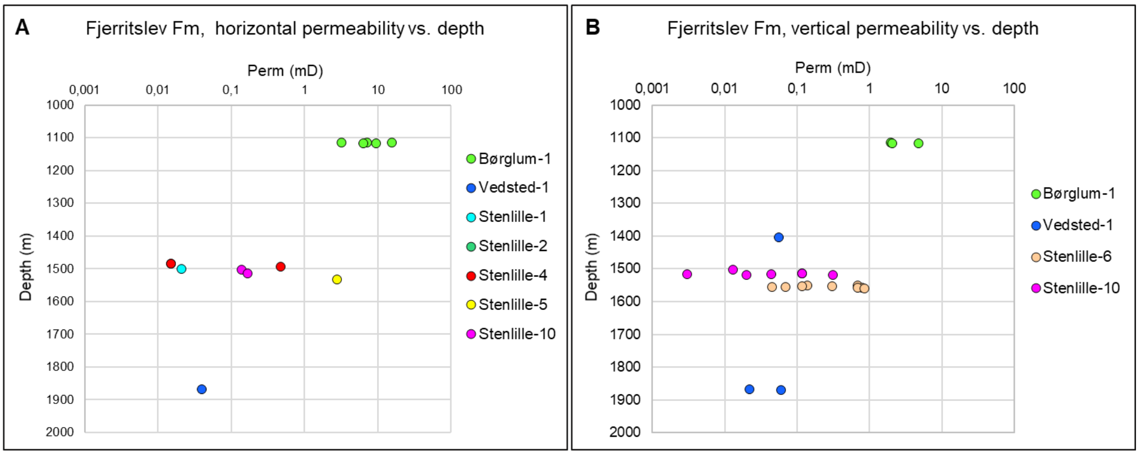


Figure 3.3. *Data from core analyses of the Fjerritslev Fm:* ***A****. Horizontal permeability vs. depth,* ***B.*** *Vertical permeability vs. depth (Pedersen et al., 2021). Note that all analysed samples are from depths of 1100 meters or more and therefore do not represent direct analogues for claystones occurring at 500 meters depth.*

In the Lower Jurassic Fjerritslev Formation, smectite occurs in amounts ranging from 1% to more than 40%. The variation appears to be both stratigraphic and geographic, however there are no systematic studies on the presence of smectite in the Fjerritslev Formation. In samples from the Rødby-1 well on the island of Lolland, the Fjerritslev Formation generally contains 30-40% smectite. In the Frederikshavn-1 and Fjerritslev-2 boreholes in northern

Jylland, the smectite content varies from 1% to > 40%, where the upper part of the Fjerritslev Formation has a low content varying from 0 to 10%, and the deeper part contains up to 40%. The Ørslev-1 well has a low content of 1–10% smectite, possibly due to the fact that the Fjerritslev Formation here is dominated by silt and has a relatively low content of clay sized grains (Report no. 4, cf. reference in Chapter 8.1).

Kaolinite typically constitutes a large proportion of the clay content, ranging from approximately 8% in the Rødby-1 well on Lolland to 20–27% in northern Jylland. Calcite is generally not present in the Jurassic sediments and traces of calcite (<1%) have been reported from only a few samples. The Upper Jurassic succession is dominated by sandstone and there is no data on Upper Jurassic claystones.

In the Lower Cretaceous succession, the amounts of clay and smectite vary significantly. In the Fjerritslev-2 well in northern Jylland, claystone with approximately 40% clay minerals - mainly illite, chlorite and kaolinite, small amounts of smectite and traces of calcite are reported. Claystone from the Rødby-1 well on Lolland contains 30–40% clay minerals, of which kaolinite constitutes the majority and illite, mica and chlorite constitute a few percent each. The smectite content varies from 1% to 25%, with the lowest content in the Sæby-1 borehole in Nordjylland and the highest measured in the Rødby-1 well on Lolland.

In Lower Cretaceous claystones, kaolinite typically constitutes up to 15–20% and as much as 33% of the total clay volume. The amount of calcite varies between 1% and 14% in the Rødby-1 and Sæby-1 boreholes.

3.3 Upper Cretaceous and Paleogene carbonates (Chalk Group)

In the present study, the term carbonate is used for the calcareous rocks of the Chalk Group. These include Danian carbonate sand, limestone, marl (clay rich carbonate) and bryozoan chalk, and Upper Cretaceous chalk, which is dominated by a fine-grained coccolith matrix and varying amounts of clay (marl). An outcrop example of interbedded grey marl and white chalk is seen in Figure 3.4, and a carbonate rock composed of pure white chalk exposed in a quarry in Stevns is seen in Figure 3.5. A summary of the Chalk Group's geology is presented in Report no. 3 (cf. reference in Chapter 8.1).

In areas where carbonates from the Chalk Group constitutes near-surface groundwater reservoirs, there is abundant data on the physical properties of the carbonates, including permeability, porosity, and fracture characterization. The present knowledge of hydraulic conductivity and effective porosity of carbonate in the groundwater zone when carbonates from the Chalk Group occur at depths of 50 to 100 meters below ground level is presented in Kidmose et al. (2021). In contrast, there is very little knowledge about the properties of carbonate in the 100 to 600 meters depth interval. One important data point is the Stevns-1 borehole, where a detailed data set is provided based on core analysis and borehole measurements. The dense data collection in the Stevns-1 well, which is drilled to 460 meters, enables a correlation between measured physical parameters and geological parameters such as stratigraphy, clay content and clay mineralogy - and to seismic data and geophysical parameters (Nielsen et al., 2011).

Figure 3.4. *Outcrop of the Rørdal Member exposed in the Rørdal quarry near Aalborg, showing interbedded layers of light, clean carbonate, and darker layers of marl (clay rich chalk), (photo: Erik Thomsen). The exposed section is 16–18 meters high.*

Figure 3.5. *Pure, white carbonate from the Sigerslev Formation exposed in the Sigerslev quarry at Stevns. The outcrop is approximately 20 meters high. Photo: Peter R. Jakobsen.*

Porosity and permeability

The hydraulic properties of a carbonate rock depend on the matrix properties and whether open fractures occur. Groundwater extraction from carbonate is dependent on the presence of open fractures and is generally limited to the upper 50 meters of the carbonate sections. Carbonates generally become harder and denser the deeper they are buried.

A plot of permeability as a function of porosity for carbonates in the Stevns-1 and Erslev boreholes shows a correlation between high porosity and high permeability and generally decreasing values with increasing depths (Figure 3.6 and 3.7). When the porosity of the carbonate can be interpreted from petrophysical logs, the permeability can be estimated with some accuracy as in general there is relationship as shown in Figure 3.8. Measurements from the Erslev boreholes show lower permeabilities compared to the Stevns-1 borehole for the same depth, which may be a result of analyses carried out on samples from different stratigraphic intervals and / or that diagenetic processes are different in the two areas (Erslev is in Nordjylland and Stevns is situated in the southeastern part of Sjælland).

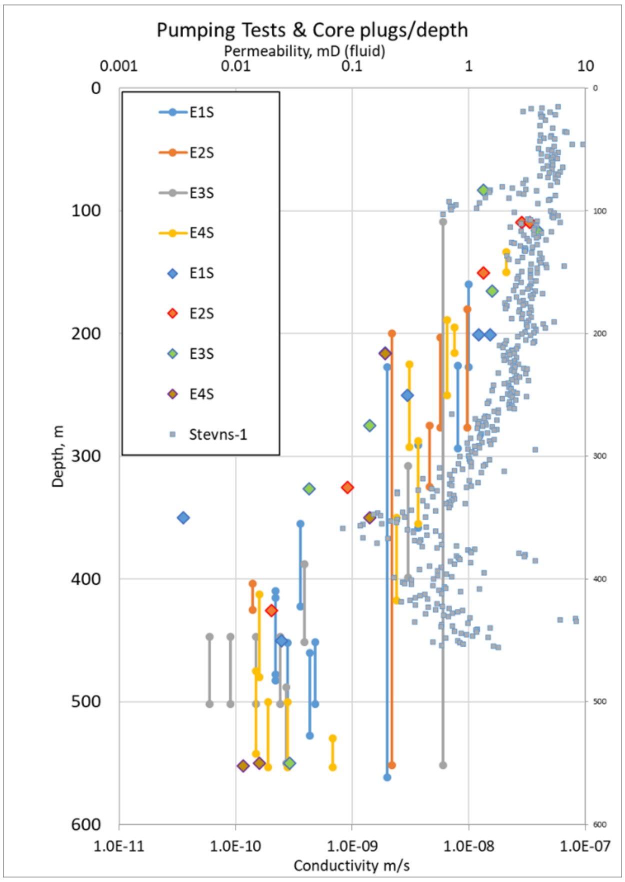


Figure 3.6. *Comparison of matrix permeabilities measured from core samples from the Erslev wells, interval permeabilities interpreted from well tests, and core analyses from the Stevns-1 well. The gas permeabilities are converted to fluid permeabilities. A permeability of 1 mD corresponds to a hydraulic conductivity of* $1*10^{-8}$ *m/s (Report no. 3).*

Danian carbonates, which constitute the youngest (uppermost) stratigraphic unit of the Chalk Group, generally have significantly higher permeabilities for a given porosity value than is observed from the deeper layers (Figure 3.8). This is because the Danian carbonate is composed mainly of bryozoan limestone, which has a coarser grain size than the underlying (older) formations.

In boreholes where drill cores do not exist for accurate determination of porosity and permeability, a qualitative assessment of carbonate permeability and capability of retardation can be made based on estimates of clay content in the carbonate. The clay content can be assessed from gamma logs and from qualitative descriptions of cuttings (small rock fragments from the drilling processors) from boreholes. Thus, it can be assumed that intervals in the Chalk Group, where well logs show high gamma readings will comprise clay, and thus have a relatively low porosity and permeability (as seen in Figure 3.7) compared to clean carbonate rock. Grey cuttings in the Chalk Group are usually reported from intervals with high gamma-readings and can be used as an independent indication of marl, i.e. carbonate rock with a relatively high content of clay minerals.

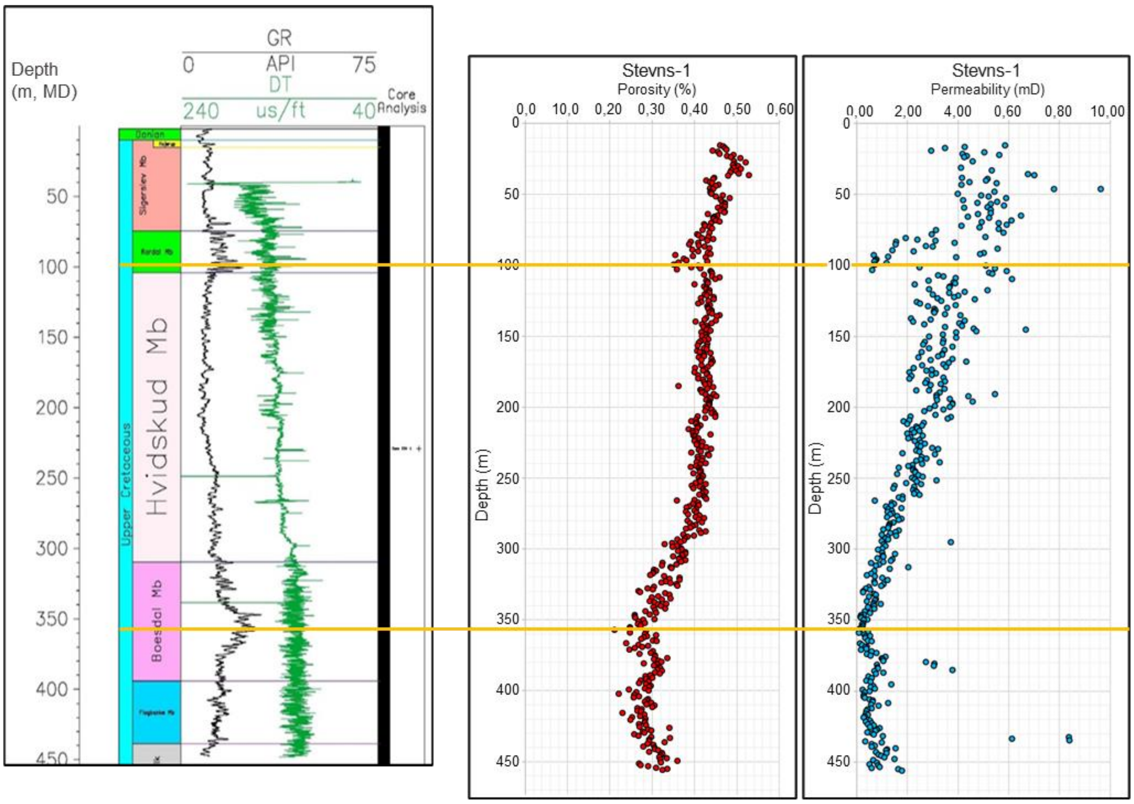


Figure 3.7. *The figure to the left shows two combined petrophysical logs (gamma log GR, and sonic log representing 1/sound velocity, DT) from the Stevns-1 borehole (Kristensen et al. 2016). A high clay content is interpreted where GR-readings are high, at the depths marked with yellow lines. The high clay content coincides with low porosities and permeabilities as plotted in the diagrams to the right (Mortensen et al., 1998). Generally, such a correlation between low porosity and permeability, and high clay content is expected as clay rich sediments show a high degree of compaction due to the minerals' plate structure. The increased amounts of clay in the Stevns-1 well occur in the Boesdal Member and Rørdal Member, which are known from other areas to comprise significant amounts of clay (see also Report no. 3).*

Only few analyses of clay content and clay minerals have been carried out on samples from the carbonates. Data show that there are generally 0.05–5% clay minerals and up to 2% smectite in the white, and cleaner intervals of the carbonate. The grey intervals contain 3–15% clay minerals and a total of 2–8% smectite. The content of smectite typically constitutes 50% or more of the total clay content. It can therefore generally be expected that grey, clay rich intervals in the carbonate contain between 2–8% smectite. The clay rich intervals in the carbonate can be identified from good quality, high resolution gamma-logs and by the presence of grey carbonate cuttings from boreholes.

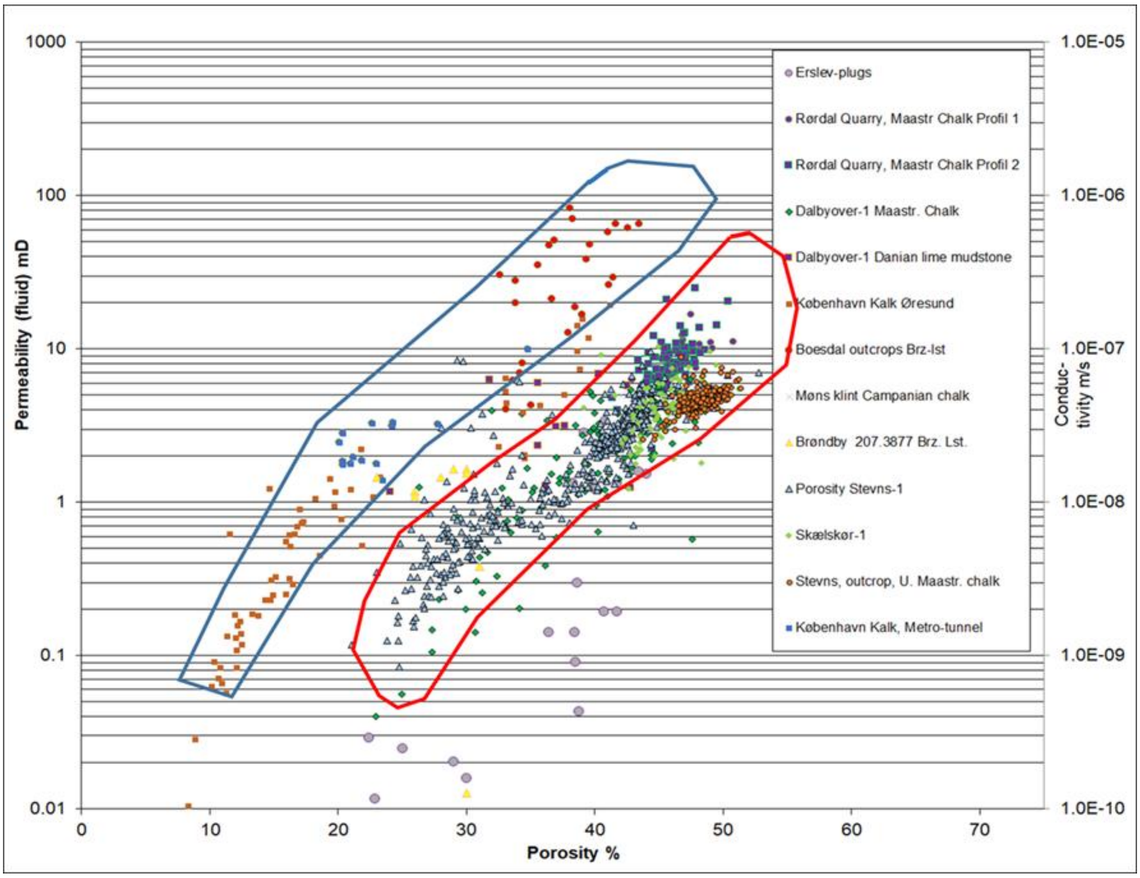


Figure 3.8. *The diagram shows the correlation between porosity and permeability for different sections of the Chalk Group. Data points outlined by the blue polygon are from the younger Danian bryozoan chalk, and data points outlined by the red polygon are from the older and generally more fine-grained carbonate sediments from the Upper Cretaceous (see Report no. 3). The axis to the right shows hydraulic conductivity calculated from permeability.*

3.4 Numerical modelling of barrier effectiveness

Preliminary investigations of the barrier effectiveness of claystones and carbonates have been carried out from conceptual 1D numerical modeling of nuclide transport. The models represent average conditions for the geological record in the Danish subsurface. The model is made for two scenarios, where carbonate and claystone, respectively, constitute the host rock in the depth interval 400 to 500 meters. In both scenarios, carbonates constitute the barrier rock in the ECZ in the depth range from 400 to 140 meters. The upper 140 meters represent the section, where groundwater reservoirs may occur in carbonate and Cenozoic sand and this section is therefore not regarded as having potential to provide barriers in the ECZ.

The conceptual numerical modeling of carbonate and claystone host rocks is performed with stochastically varied hydraulic conductivities in the individual geological layers in scenarios with different transport parameter values and boundary conditions. The modeling is conservative, which means that the results reflect simulated transport times for a nuclide, assuming the least favourable conditions for retardation. For example, the nuclide transport is simulated without including sorption, which would cause greater retention and thus longer transport times. Density effects, which will further delay any transport of nuclides, are omitted in the initial modeling. Finally, the vertical gradients express an upwards flow from a depth of 500 meters, which is a conservative assumption that does not apply to all areas.

The modeling of a carbonate host rock showed that the average time for maximum concentration reaching the groundwater reservoir ranges from thirty-three thousand to more than five hundred thousand years in the different scenarios. With a claystone host rock, the average maximum concentration does not reach the groundwater reservoir within 1 million years. The modeling of both carbonate and claystone host rocks shows that determination of hydraulic gradients, which is site specific, the hydraulic conductivity, and diffusion coefficients used to simulate representative transport times for nuclides, are crucial for the modeling results. The modeling in the present project phase is conceptual and not site-specific and shows that both carbonates and claystones can be regarded as potential host rocks. At the same time, the modeling results show the importance of determining specific properties for nuclides related to e.g. solubility of a given nuclide.

3.5 Precambrian crystalline basement

Different types of granite and gneiss have been identified in the basement on the Island of Bornholm based on mineral composition, grain size and structures. The mineralogy and distribution of the various rock types is described in Report No. 5 (c.f. reference in Chapter 8.1). All the crystalline rocks were formed during several events of magma intrusion and cooling over a relatively short time-period from 1460 to 1450 million years ago. The boundaries between the different rock types vary from sharp to gradual, locally with intrusions of the adjacent rock type. Since all the rocks are formed by intrusion of magma, both vertically and horizontally, it should be expected that the distribution of the different types of granite / gneiss in the subsurface will be different from the distribution at ground level.

A summary of the rock forming minerals generally constituting more than 1% of the rock volume, is shown in Table 3.1. In addition, magnetite, titanite and apatite typically make up 1% or less, but locally up to 3% of the rock volume. Accessory (trace of) minerals include hypersthene, diopside, fluorite, muscovite, zircon, epidote, chlorite, allanite, gadolite, and titanite.

Weathering of rock surfaces in natural exposures and along fractures results in the formation of minerals such as iron and manganese oxides, kaolinite, sericite, and greenish clay with chlorite. In banded rocks, the dark minerals are less resistant to weathering compared to light coloured minerals, which causes a fissile surface expression.

Tabel 3.1. *Overview of minerals that constitute the major part of the crystalline rock types (1 % volume or more). Accessory minerals typically constitute less than 1 % of the rock but locally as much as 1–3 %. For banded rocks and migmatites a volume range is given due to variations in different parts of the rocks (the table is based on data presented in Report no. 5 and references herein (cf. references in Chapter 8)).*

	Quartz (%)	Plagioclase (%)	K-feldspar /Perthite (%)	Biotite (%)	Hornblende (%)	Grain size	Intrusives
Bornholm Gneiss	29-72	12-31	11-38	1-8	0-1	Fine – coarse, foliated – banded	Diabase up to 60 m wide, aplite, pegmatite
Rønne Granite	21	30	29	5	10	Medium	Pegmatite, diabase
Paradisbakke Migmatite	23-60	25-40	35-60	7	8	Fine – medium, foliated	Pegmatite and aplite, sand-filled fractures
Vang Granite	27	22	33	6	5	Medium - coarse	Pegmatite, aplite, dikes
Svaneke Granite	25	26	36	7	2	Coarse	Pegmatite, aplite, dikes, sand-filled fractures
Hammer Granite	33	18	41	4	1	Fine – medium	Pegmatite and aplite
Almindingen Granite	33	18	41	4	1	Medium - coarse	Diabase

Rock properties

Matrix porosity in crystalline rocks is usually less than 1% and is related to open inter- and intragranular microfractures. In a homogeneous unweathered crystalline rock (an example is shown in Figure 3.9), the matrix permeability is usually extremely small and nuclide transport will occur by diffusion. Major fractures in crystalline rocks are typically generated from processes such as contraction due to cooling, and tectonic stress and pressure relief during uplift and erosion. Depending on the geological setting and development, these fractures may "self-heal" by minerals precipitated from percolating water. If the rock is cut by fractures or faults, it may result in a significant fracture permeability and enable fracture flow.

In natural exposures and quarries it is seen that the upper 50 – 100 meters of the basement on Bornholm is often penetrated by horizontal and vertical fractures, but there is no data from greater depths. Fractures and faults cross-cut structures and stratification in gneisses and boundaries between different rock types. This indicates that structures in the crystalline rocks had no influence on the occurrence of, or the orientation of fractures. The fractures are interpreted to be of tectonic and glacial origin (Report No. 5, cf. reference in Chapter 8.1). The occurrence of dikes is associated with extensional faults and fractures where the rock has been exposed to stretching.

Figure 3.9. *Unweathered Paradisbakke migmatite, Paradisbakkerne area, Bornholm. Photo: Peter Gravesen.*

Numerical modeling of nuclide transport in granite / gneiss has not been carried out in this project phase, mainly because there is abundant knowledge from studies of the Swedish basement, which in many ways is comparable to the basement on Bornholm. Information is available from site investigations of pre-Cambrian basement in Sweden and Finland where deep repositories are being established (SKB, 2021; Posiva, 2021).

3.6 Cenozoic clay and sand (not contributing to the ECZ)

Cenozoic sediments occur at depths to 500 meters in central and western Jylland. The sediments consist of alternating layers of marine clay, deltaic sand, and fluvial sand deposits (Figure 3.10), which locally can be several hundred meters thick (Report no. 2, cf. references in Chapter 8.1).

Clay rich, laterally extensive marine sediments, which locally reach thicknesses of several hundred meters, occur in the Paleocene and Eocene formations. Locally, the formations may comprise plastic clay. Oligocene, glauconite-bearing and mica-rich clay and silt deposits with thicknesses up to 170 meters are known from the eastern and central parts of Denmark. Sand-rich sediments were deposited in a large delta system that extended from the western part of Denmark into the North Sea area. In central Jylland, the Cenozoic record contains thick deposits of fluvial Miocene sand, while the sediments to the southwest are dominated by marine clay, silt, and fine-grained sand.

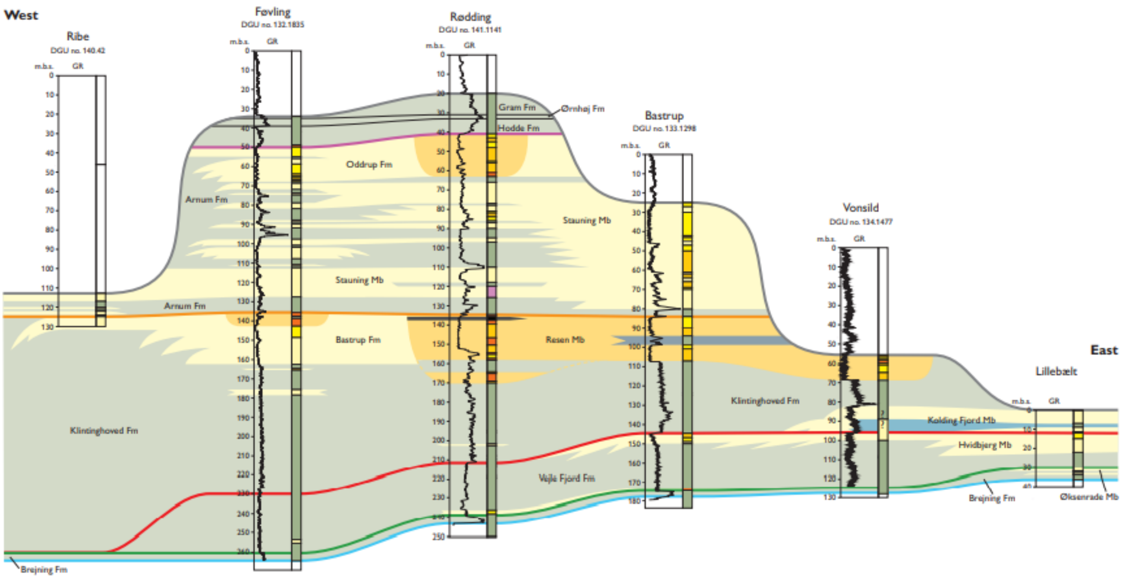


__Figure 3.10.__ Stratigraphic well log correlation showing that the amounts of sand and claystone, respectively, vary significantly both horizontally (from west to the east across southern Jylland) and vertically through the Miocene record (Rasmussen et al., 2010). The yellow and orange colours show the presence of sand and gravel, the greyish colours show mudstone dominated sediments.

Quaternary sediments

Pleistocene glacial and interglacial deposits reach maximum thicknesses of around 350–400 meters in northernmost Jylland, the southernmost parts of Fyn and in southwestern Jylland. The glacial deposits comprise alternating layers of clayey and sandy tills (moraine clays and sand) with large boulders, and meltwater deposits of gravel, sand, silt and clay. The lithologies vary significantly both in vertical sections and horizontally over short distances due to the variety of glacial processes that have eroded and deformed the near-surface layers, and also have deposited sediments.

Shallow subsurface features referred to as buried valleys, are glacially eroded valleys that have been filled with sediments. Their internal architecture and stratigraphic record reflect that several events of erosion and deposition have taken place. Many valleys are sand filled, and in some parts of Denmark they have been mapped in detail as the sand may be utilized for groundwater extraction. Some valleys are locally incised to several hundred meters below ground level (Report no. 7, cf. reference in Chapter 8.1).

To evaluate the risk of future erosion into the geological barriers of a deep repository it is relevant to investigate the possibility of future, deep glacial erosion. The buried valleys are often formed from repeated events of erosion and deposition. This indicates that glacial erosion occurs preferentially in areas where former valley incision has occurred, which is often associated with topographic lows and less consolidated sediments. Additionally, the valleys seem to coincide with structural lineaments related to the presence of faults deeper in the subsurface (Report no. 7, cf. reference in Chapter 8).

4. Outlining geological areas

Based on the geology and the structural framework of the depth interval 0 to 500 meters, the Danish onshore area has been divided into eleven areas. Each area is characterized by the presence of a specific potential host rock of either Jurassic and Lower Cretaceous claystone, Upper Cretaceous carbonate, or crystalline basement, at depths around 500 meters (Chapter 3). Additionally, the structural framework and complexity of the area has influence on the horizontal continuity of the potential host rock as well as formations in the overlying sections. The concept of host rock and barriers in the effective containment zone (ECZ) is illustrated in Figure 2.3 (see also Figure 5.1 in Chapter 5). Crystalline rocks occur at shallow depths only on the island of Bornholm. Where the top of the basement is near to, or at ground level, crystalline rocks will constitute both the potential host rock and the barrier in the ECZ.

To provide an overview of the regional distribution of geological formations the depth and thickness maps of the major stratigraphic units are presented in the following section. The maps are presented together with an explanation on how the information should be read. In chapter 6 the same thematic maps are presented in more detail for each area to illustrate local conditions and variations. The maps form part of the data used for the evaluation of the extent to which the defined criteria are favourable in each area. In addition, the detailed maps can be used when specific sites for the detailed geological surveys are to be identified and delineated. The geological record and the structural framework of the areas is illustrated by representative cross-sections from different parts of Denmark.

The eleven areas are presented at the end of this chapter together with a brief geological characterization with references to geological maps and cross-sections that illustrate the geology in the area.

4.1 Subsurface distribution of geological formations

The distribution of stratigraphic units in the Danish subsurface is illustrated in the regional geological cross-section in Figure 4.1. It is seen that the Jurassic and Cretaceous formations are widespread along the entire length of the cross-section, with greatest thicknesses in the Danish Basin, where they also occur at the greatest depth. The Upper Jurassic interval is in many areas absent, or so thin that it cannot be mapped seismically. Maps and cross-sections therefore show the combined Lower Cretaceous and Upper Jurassic section’s thickness. Cenozoic sediments are present with great thicknesses in the southern part of the section in the Danish Basin and on the Ringkøbing-Fyn High, while the interval is thin or absent on the Skagerrak-Kattegat platform to the north.

The stratigraphic units and subsurface structures have been mapped based on seismic data and deep boreholes (Report no. 6, cf. reference in Chapter 8.1). In addition, thousands of shallow groundwater wells have been used to map the Quaternary section that generally occurs in the uppermost 0 to 100 meters of the record and only locally to greater depths (Report nos. 2 and 7, cf. reference in Chapter 8.1).

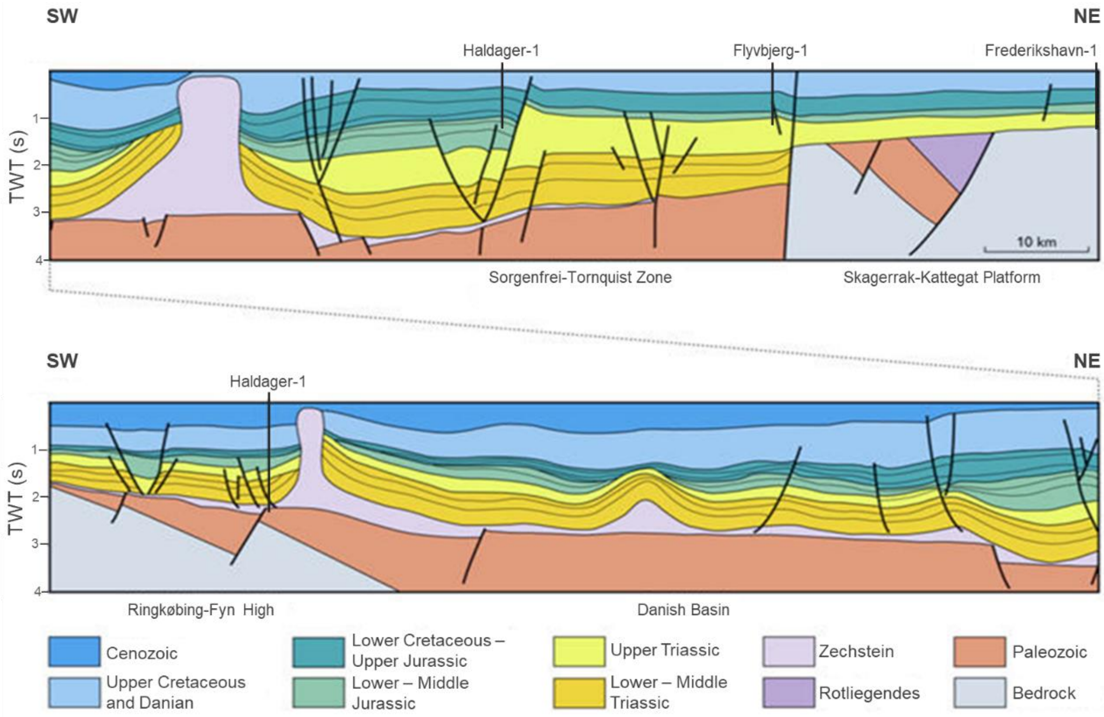


Figure 4.1. *Geological cross-section showing the uppermost ca. 8 kilometers of the record. It extends from the Skagerrak-Kattegat Platform in the northeast (NE), across the Sorgenfrei-Tornquist Zone and the Danish Basin to the margin of the Ringkøbing-Fyn High to the south-west (SW) (From Nielsen, 2003). The vertical scale is "Two Way Travel time" (TWT) – measuring the time in seconds it takes for an acoustic wave to reach a major geological boundary and travel back to surface. For location see Figure 4.2.*

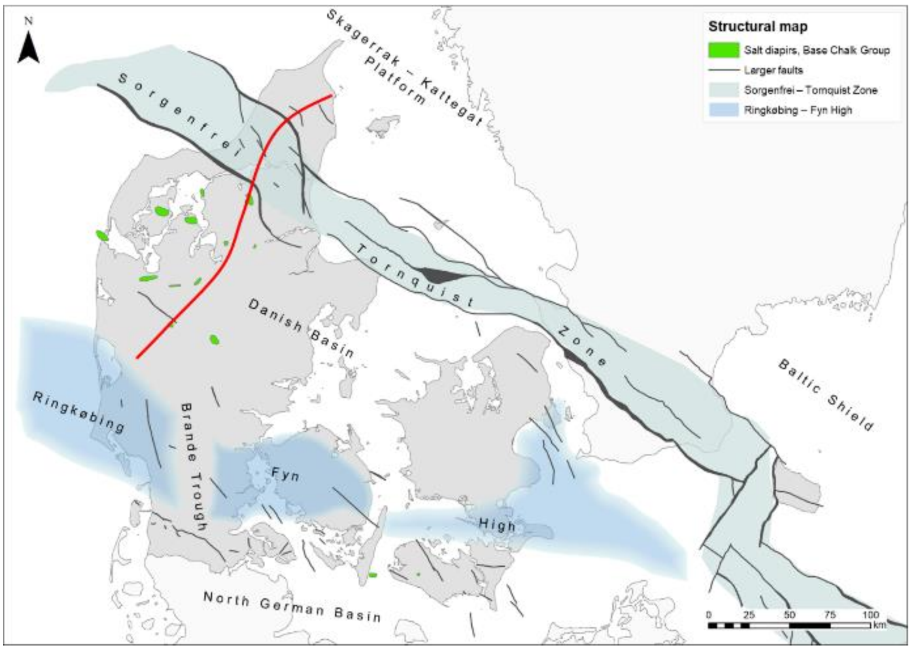


Figure 4.2*. The location of the NE to SW oriented regional cross-section in Figure 4.1 is displayed with a red line on a structural map. The structural elements have a significant influence on the distribution and thickness of sedimentary deposits in the subsurface.*

4.2 Introduction to the geological maps

The geological maps are based on interpretation of seismic data and data from deep bore holes, as presented in detail in Report No. 6 (cf. references in Chapter 8.1). The map in Figure 4.3 shows the seismic data base and the varying density and quality of data is indicated with different colours. The seismic data is collected mostly for projects focussed on targets at several kilometres' depth related to oil and gas exploration, gas storage and geothermal projects. The shallow seismic data are acquired mainly for groundwater exploration and geotechnical surveys and are generally of high quality (high resolution). The deep boreholes are unevenly distributed, with data of varying quality and level of detail. Most boreholes have been drilled to test the presence of reservoir sandstone, whereas data from tight claystones and carbonates have been of little interest and less data have been acquired from these fine-grained sediments.

Geological maps showing the depths to the major geological unit boundaries, top Chalk Group (Danian - Upper Cretaceous), base Chalk Group (top Lower Cretaceous), top Fjerritslev Fm (top Lower Jurassic) and base Jurassic (top Gassum Formation) are shown in Figures 4.4–4.7. The mapped stratigraphic units are identical to those shown in the regional cross-section in Figure 4.1.

The depths refer to ground level, as the focus of this project is formations and rocks occurring at depths to 500 meters below ground level. Contours on geological depth maps are usually with reference to sea level (mean sea level, msl), therefore, if maps from the present study are compared with geological depth maps produced for other purposes, the depths will be different if they do not have the same reference level. On the maps, the coastlines are indicated with a white line. The depths to the various geological units are also shown for the near coastal areas to illustrate that the geology is continuous in the subsurface regardless of the shoreline position and to indicate that offshore seismic data are also used for the geological mapping. The seismic units have not been mapped on Bornholm, as deep seismic data only exist from the sedimentary basins offshore Bornholm (Fig. 4.3). However, a map of the Cenozoic interval on from Bornholm has been mapped based on borehole data.

All depth maps (Figure 4.4–4.7) are displayed with the same colour scale, showing depths from 0 meters (ground level) to more than 1500 meters. It should be noted that for depths exceeding 700 meters, each colour represents a depth range of more than 100 meters.

The colour scale for the thickness maps (Figure 4.9–4.12) ranges from 0 meters to more than 1500 meters and the same scale is used for all thickness maps. The different colours on the colour scale represent different thicknesses, where the interval 0 to 200 meters is divided into 50 meters intervals, i.e., thinner intervals than for the rest of the scale bar. This subdivision is made to enable the identification and distinction of areas where the thickness of stratigraphic intervals with potential host rock is 100 meters thick or more.

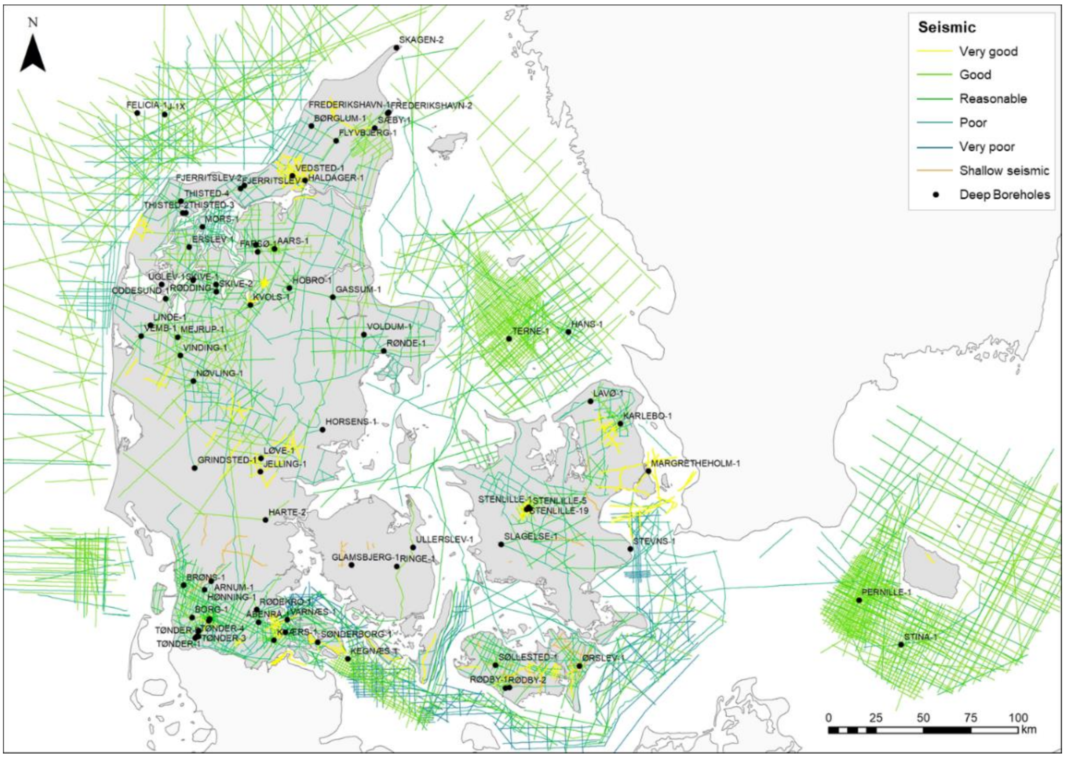


***Figure 4.3**. Overview map showing the seismic database and location of deep boreholes. The map illustrates a highly varying data density across Denmark and the colours indicate the varying data quality; the yellow and light green colours represent high quality data. Detailed maps for local areas are presented in Chapter 6.*

The depth and thickness maps produced from regional mapping of seismic data, are associated with uncertainty resulting from the variable distance between the seismic lines, the distance to well data, and the varying data quality (Figure 4.3). The uncertainty is 50 to 100 meters on depth maps, and up to 50 meters on the thickness of seismic units mapped in the depth range 0 to 800 meters (Report no. 6, cf. reference in Chapter 8.1). The uncertainty generally increases with increasing depth and increasing distance to well data. Locally, where there is a good tie to high quality well data, the uncertainty is less, typically in the order of 10–50 meters. The uncertainty is important to acknowledge when the individual areas are characterized and evaluated with regards to whether a host rock with the required thickness of at least 100 meters is present in the 400–500 meters depth range. The evaluation presented in Chapter 5 is based on the current knowledge of geological conditions in the areas. When collecting new data targeting a depth range of 0 to 1000 meters at a site, a much greater accuracy of depths and thicknesses is expected.

The depth maps (Figure 4.4–4.7) show the depth to the regionally mapped stratigraphic intervals. The top of the Chalk Group (Figure 4.4) occurs in the eastern and northern part of Denmark at depths between 0 and 100 meters and at gradually increasing depths to the west where it may exceed 700 meters in the western and southernmost part of Jylland. The base of the Chalk Group (top Lower Cretaceous) occurs in most areas at depths greater than 700 meters (Figure 4.5). The base of the Chalk Group occurs locally at depths shallower than 500 meters only in the northernmost part of Jylland and in the Lolland - Falster area. The Base Chalk Group map shows larger, mapped faults that intersect the surface. Some of the major faults are bounding larger basins and highs, and thus have a significant impact on the distribution of the sedimentary deposits and the thicknesses of the stratigraphic intervals. Numerous faults have been identified on seismic cross-sections (as illustrated in Chapter 4.3) but are not mapped in detail due to lack of data and are therefore not shown on the geological maps.

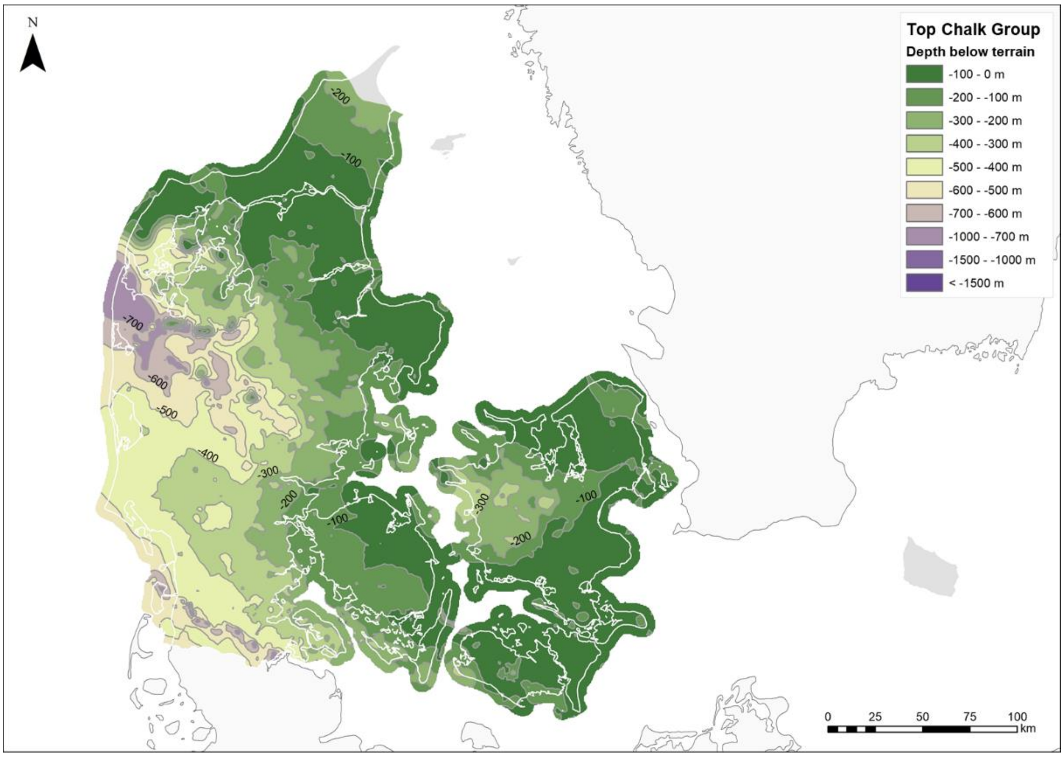


Figure 4.4. *Top Chalk Group depth map. The map shows that the depth to top Chalk Group varies from 0 to 100 meters in eastern and northern parts of Denmark (dark green) to more than 700 meters in the western area (light purple colours).*

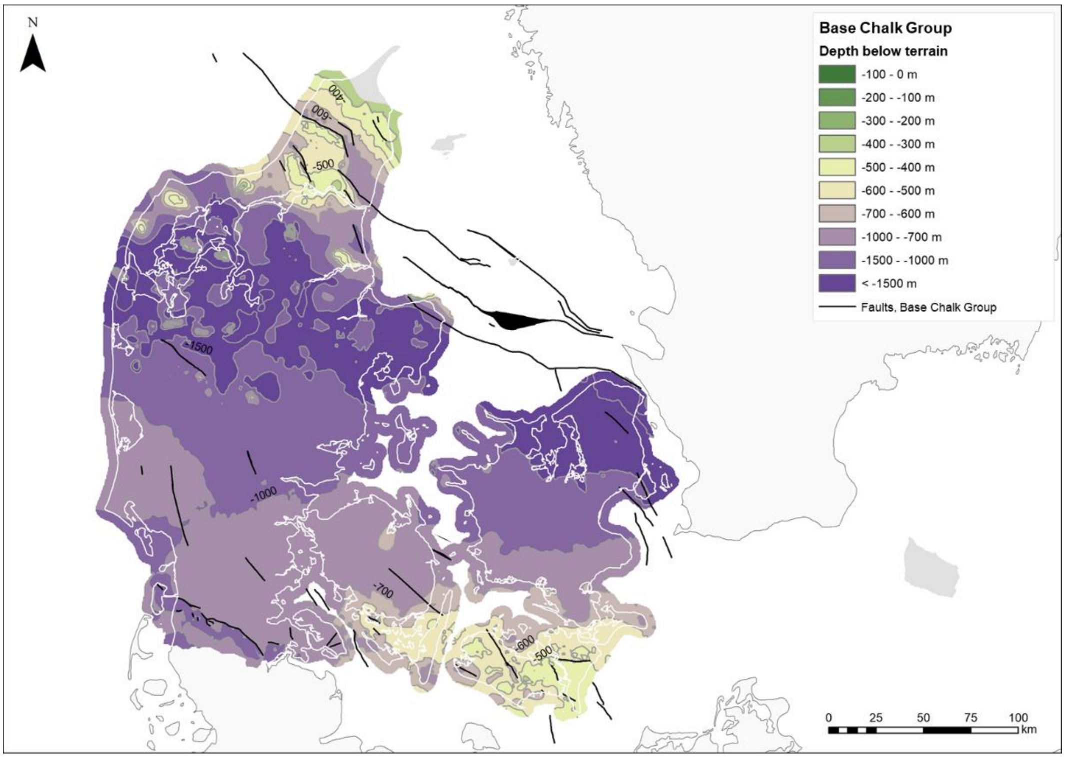


Figure 4.5. *Base Chalk Group (Lower Cretaceous) depth map. The map shows that the base of the Chalk Group only locally occurs at 400–500 meters depth in northern Jylland and the southeastern parts of Denmark (yellow to green areas) and otherwise is generally deeper than 600 meters (purple areas).*

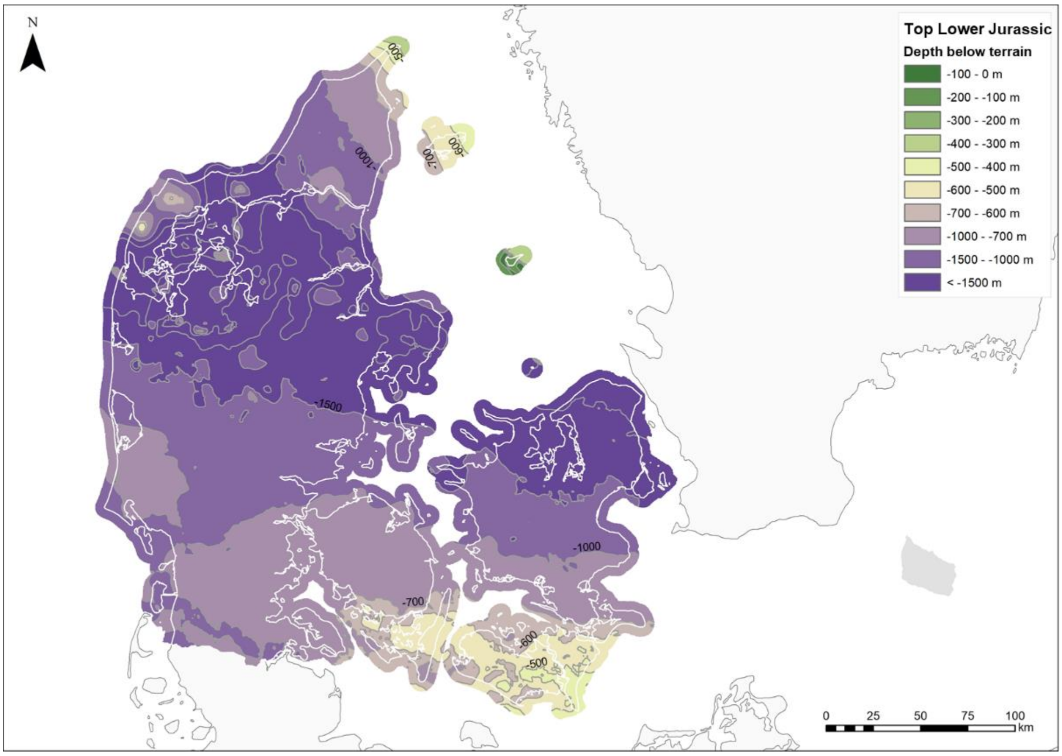


Figure 4.6. *Top Lower Jurassic depth map (Top Fjerritslev Formation). The map shows that the Top Lower Jurassic generally occurs at depths exceeding 700 meters and only locally at 400–500 meters depth (yellowish colours).*

The base of the Jurassic (Figure 4.7) occurs at depths around 600–700 meters locally in the Lolland-Falster area, but generally it occurs at depths greater than 1000–1500 meters.

The Cenozoic section includes Quaternary glacial deposits that constitute the uppermost, and youngest part of the record. Valleys formed from glacial erosion can be mapped from TEM data ("Transient Electro-Magnetism"), which recorded the electrical resistance in the subsurface (Report no. 7, see references in Chapter 8.1). The valleys are referred to as buried valleys and many are filled with sandy sediments. The map in Figure 4.8 shows the extension of the TEM database and buried valleys that are mapped mainly from TEM data. The map shows the horizontal extent of the valleys, but not the depth to the base of valleys, which can be determined from seismic and well data.

The total thickness of the Cenozoic section is shown in Figure 4.9. In the eastern and northern part of Denmark, the thickness is generally less than 200 meters, while thicknesses of more than 500 meters occur locally in the western and northernmost parts of Denmark. The Chalk Group occurs extensively, with highly varying thicknesses (Figure 4.10) from more than 1500 meters in the central-northern Jylland and northern Sjælland. The thickness is decreasing towards the northern and southernmost areas where it typically less than 500 meters. The Chalk Group wedges out in the northernmost part of Jylland and north of Frederikshavn it is absent.

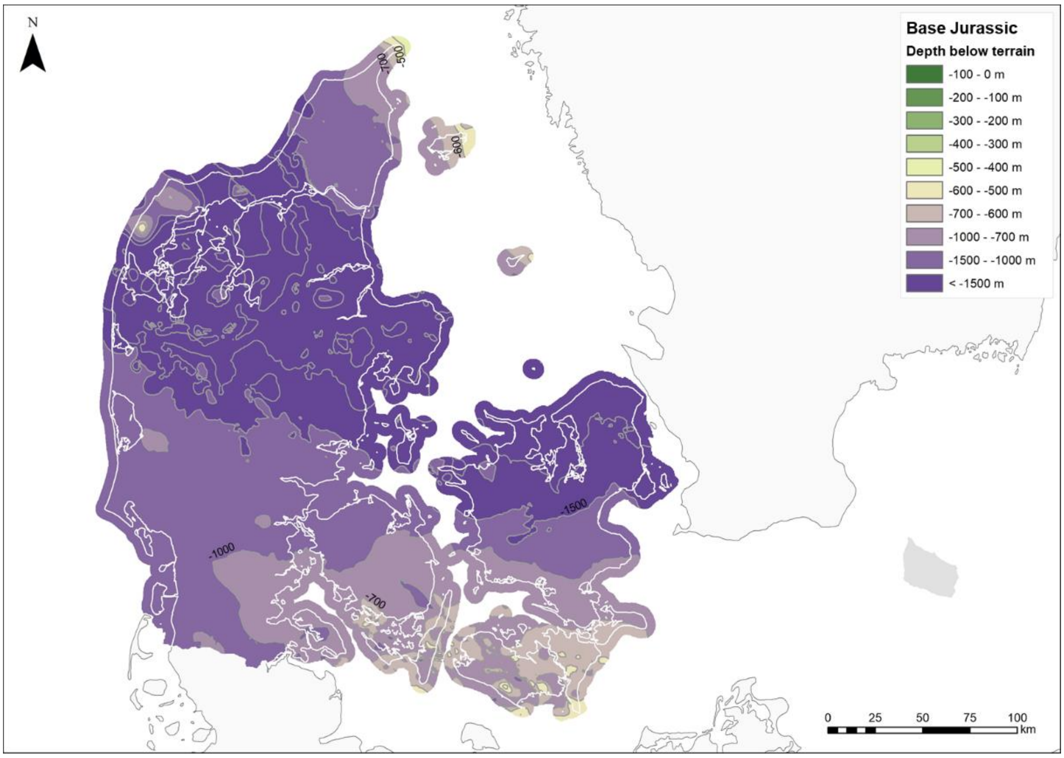


Figure 4.7. *Base Jurassic depth map. The map shows that the depth to base Jurassic varies from more than 1500 meters in central parts of Jylland and northern Sjælland (dark purple areas) to 600–700 meters towards the southeast and in northernmost part of Jylland.*

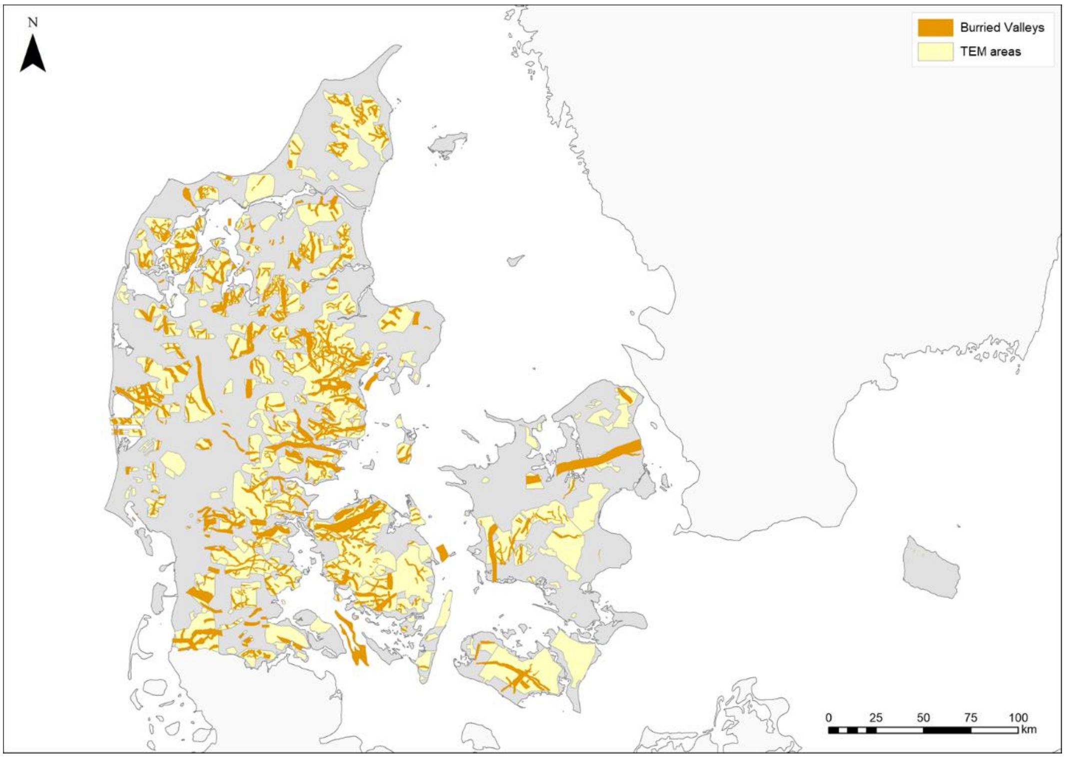


Figure 4.8. *Map showing the extension of TEM data (yellow) and mapped buried Quaternary valleys (orange) (Sandersen et al. 2021).*

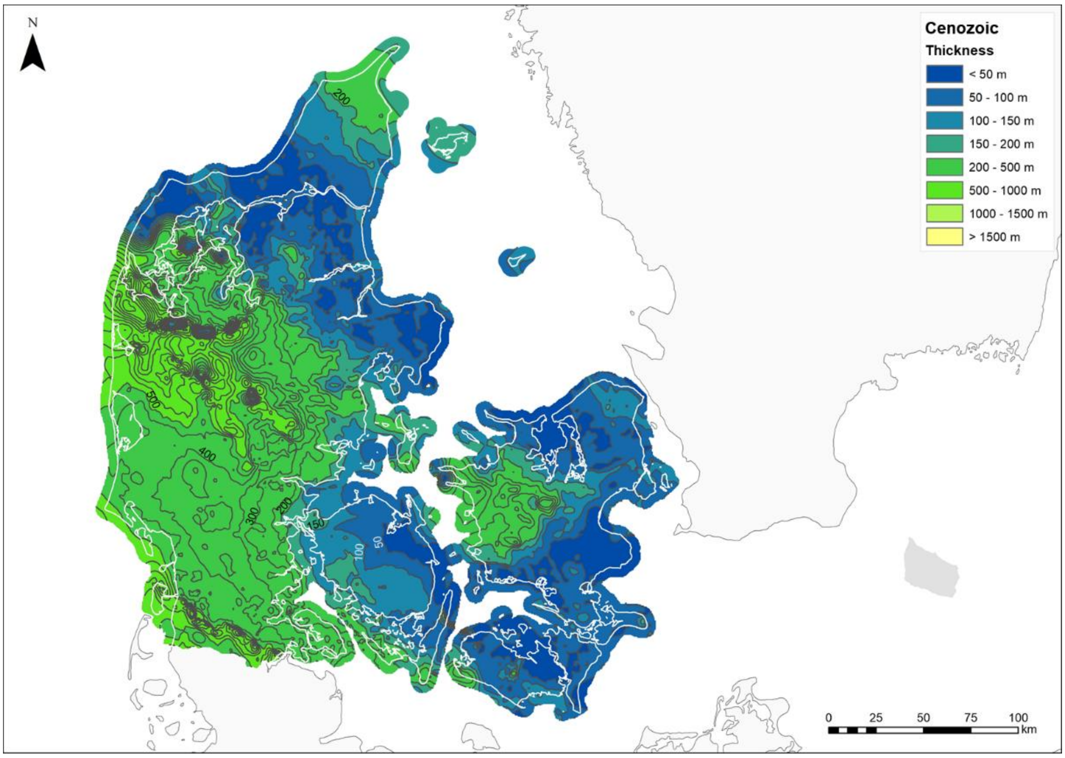


Figure 4.9. *Cenozoic thickness map. The map shows that the thickness varies from 0–100 meters in the northern and eastern parts of Denmark (blue areas) to more than 500 meters locally in western Jylland (light green areas).*

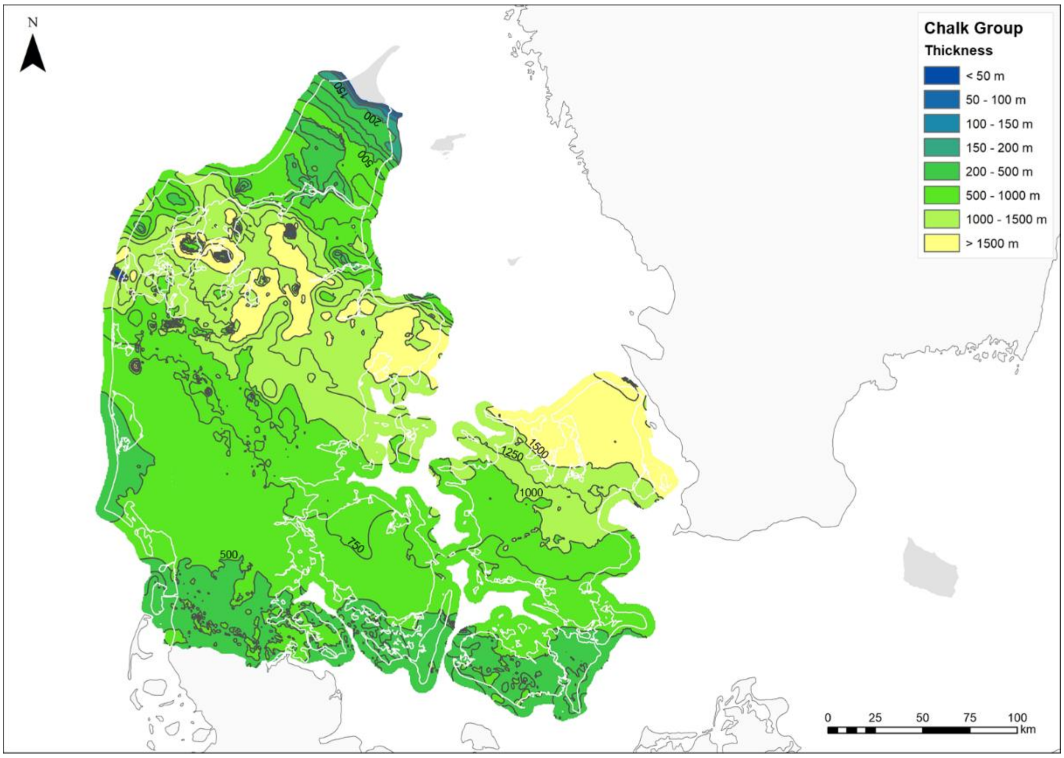


Figure 4.10 *Chalk Group thickness map. Greatest thicknesses of more than 1500 meters occur in a WNW-ESE trending area across Denmark (yellow areas). The thickness decreases to 200–500 meters both towards the north and the south (dark green).*

Upper Jurassic sediments occur only in the northern part of Jylland. In many areas the thickness is close to or below the limit of seismic resolution, therefore the combined thickness of the Middle and Upper Jurassic, and Lower Cretaceous sections is shown (Figure 4.11). To the south the Lower Cretaceous - Upper Jurassic interval is very thin (less than 50 meters, dark blue areas, Figure 4.11) and claystone sections from this interval do not fulfil the 100 meters thickness requirement for potential host rock. However, when combined with claystones in the Lower Jurassic section, there may be areas where the total thickness of claystone is 100 meters or more. Therefore, a map of the total thickness of the Lower Cretaceous and Jurassic intervals is also presented (Figure 4.12).

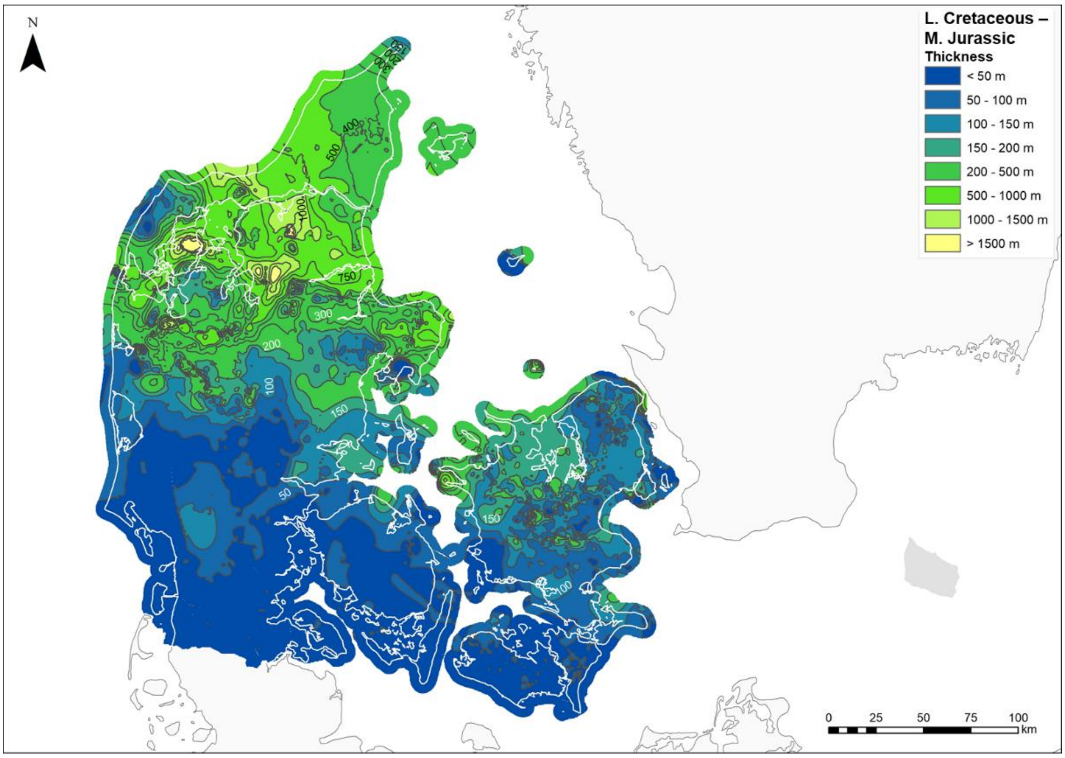


Figure 4.11. *Thickness map of the Lower Cretaceous to Middle Jurassic interval. Thicknesses exceeding 1000 meters occur locally in northern Jylland (yellow areas) but generally the interval is less than 200 meters thick (blue areas).*

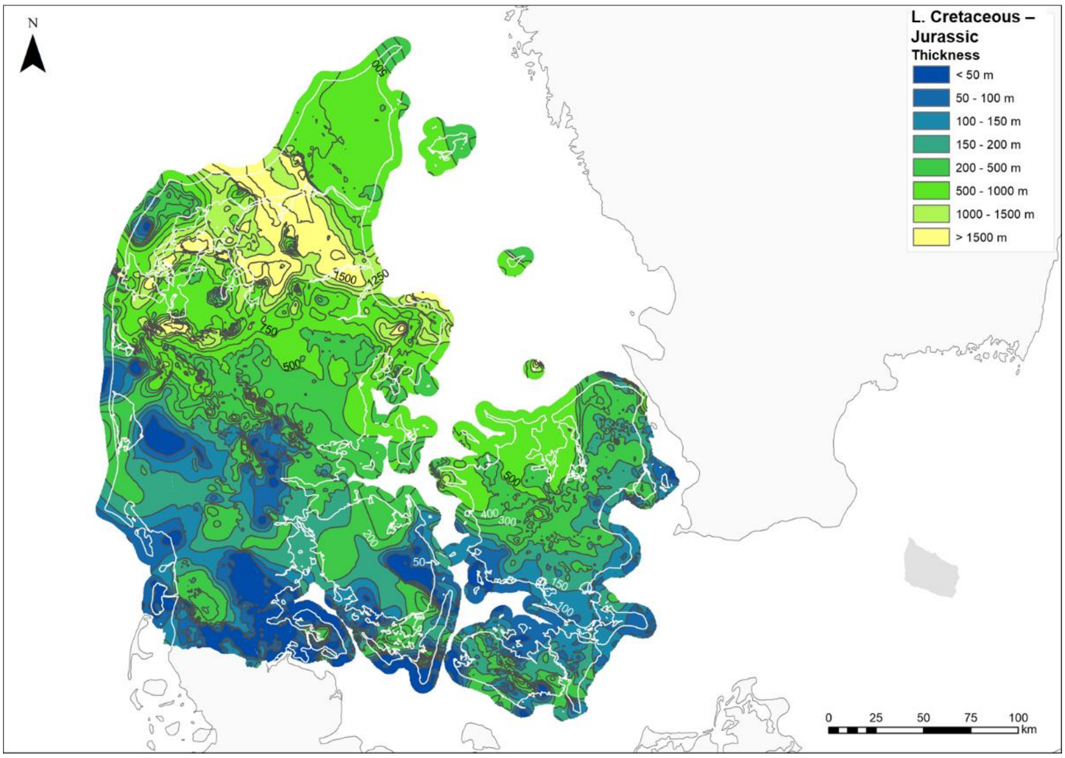


Figure 4.12. *Thickness map of the combined Lower Cretaceous and Jurassic sections. In southern Denmark, the thickness is 0 to 200 meters (blue areas), but generally the section has a thickness of several hundred meters (green areas) and locally reaches more than 1500 meters (yellow areas).*

4.3 Geological cross-sections

Geological cross-sections are presented to illustrate the structural and stratigraphic framework of the subsurface and how it varies across Denmark. Focus is on the stratigraphic intervals occurring in the depth range 0 to 600 meters and the structural elements (basins, highs, and fault zones). The selection of representative seismic lines which the cross-sections are drawn from, is partly determined by the availability of seismic data in the different areas. Where data exist from deep boreholes along the seismic line, the borehole is shown on the cross-section and stratigraphic boundaries used for correlation to seismic data are shown with yellow markers. The geographical location of seismic lines used for the drawing of cross-sections, and the deep boreholes is shown in Figure 4.13.

The geological cross-sections are graphic representations of interpreted 2D seismic lines. The horizontal scale is in kilometers, and it should be noted that the cross-sections represent horizontal distances varying from 10 kilometers to more than 100 kilometers. The vertical scale is "two-way time" (TWT) given in milliseconds (ms), which is the unit used for measuring seismic reflections (see further explanation in Report no. 6, cf. references in Chapter 8.1). To highlight the depth interval around 500 meters, the estimated position of the 400, 500, and 600 meters contour lines are indicated with dashed lines. In areas where there is a good correlation between seismic data and borehole data, the depth indication comes with little uncertainty, whereas it is more uncertain with increasing distance to other seismic lines and wells, especially in areas with dipping formation boundaries.

The cross-sections provide insight into the structural framework, both in terms of the presence and the distribution of the various stratigraphic intervals, and the geometries as controlled by the structural development. In some areas the stratigraphic boundaries are near-horizontal. In other areas large depth and thickness variations occur within short distances, which reflect a complex tectonic history with fault activity and, in some areas, local remobilization of deeply buried Zechstein salt.

The cross-sections are described with emphasis on the upper part of the record in the time interval 0–1000 milliseconds, which comprises the depth interval from 0 meters to more than 500 meters. Additionally, the focus is on identification and characterization of faults, which are steeply dipping planes across which there have been relative displacements of the layers on either side. The displacements can be horizontal or vertical, and along the fault plane, microfractures may have formed due to fault movements. The presence of faults in an area is an indication that earthquakes have occurred in geological time. Faults are shown on the cross-sections as black lines that intersect and displace the geological formations. In areas where many major faults occur within short distances (less than 10 kilometers), it can be a challenge to identify areas with horizontally continuous host rock.

The vertical extension of faults as well as their geometries can be used to predict whether faults are still active. If the fault plane extends all the way to the surface, there is a risk that the fault is still active and that earthquakes may occur also in the near (geological) future. Faults occurring only in the deeper parts of the record have been inactive for millions of years and are generally not expected to reactivate within the time-period of natural stability required for a suitable disposal site. Finally, it should be mentioned that many of the faults seen on the geological cross-sections are not shown on the geological map (Base Upper Cretaceous). This is because in many cases there is not enough data to determine the extension and orientation of the faults in map view (2D). For example, a fault seen on a north-south oriented seismic line may have an orientation varying from NE-SW to NW-SE in a map view, and it may be misleading to draw the fault on a map without further data control. To get a more complete picture of the geological and structural complexity of the individual areas, it is therefore important to combine information from the available seismic lines with the geological depth and thickness maps.

The seismic data have typically been acquired for mapping of deeper parts of the subsurface, and data from the near-surface layers are often of poor quality that does not enable a detailed identification and mapping of faults in this part of the record. In cases where faults have been mapped to continue into the Cenozoic sections, there is a possibility that they continue all the way to the surface. Based on existing data, it is often difficult to determine whether the faults continue to the surface, but the acquisition of new seismic data targeting shallower sections is expected to enable detailed mapping of the shallower sections. The occurrence of smaller, closely spaced faults in relatively steeply dipping layers, e.g. adjacent to salt structures or in fault zones is also important to recognize. Such faults may be associated with fractures which may be open or closed depending on the present stress regime in the area.

Above each cross-section, the name of the area(s) represented is shown in blue (areas as defined in Chapter 4.5). The major structural elements as shown in Figure 4.13 are indicated below the cross-sections. Each cross-section is presented with an overview map showing the cross-section's location with a red line.

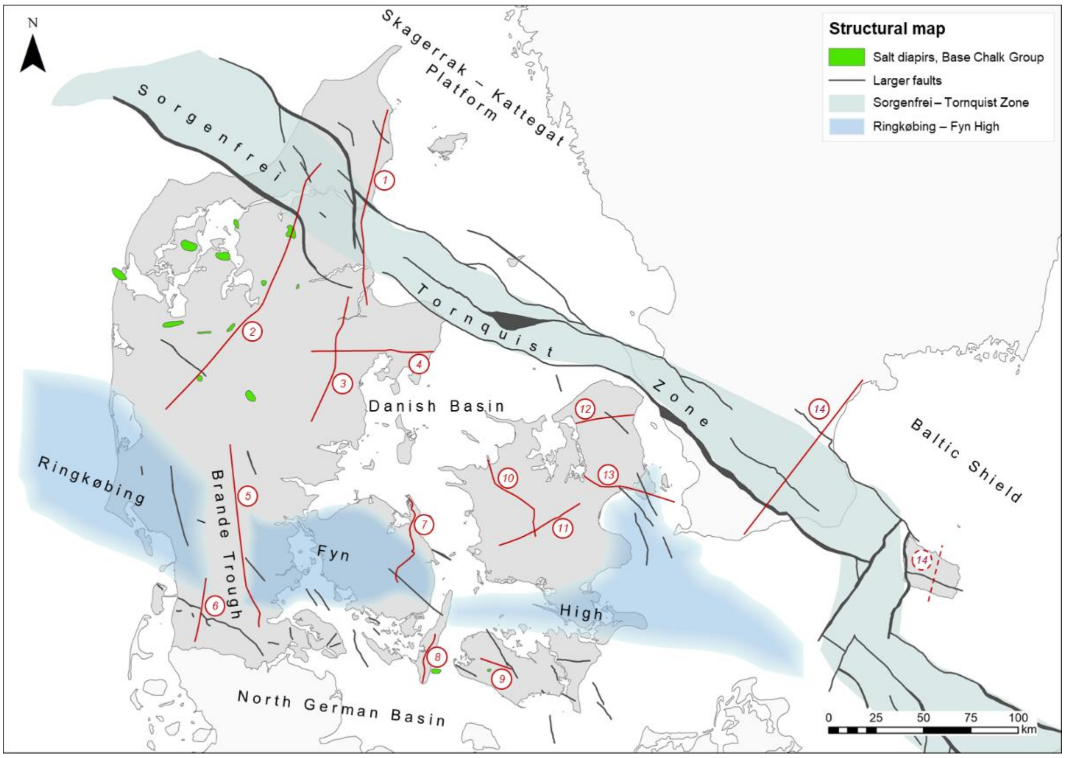
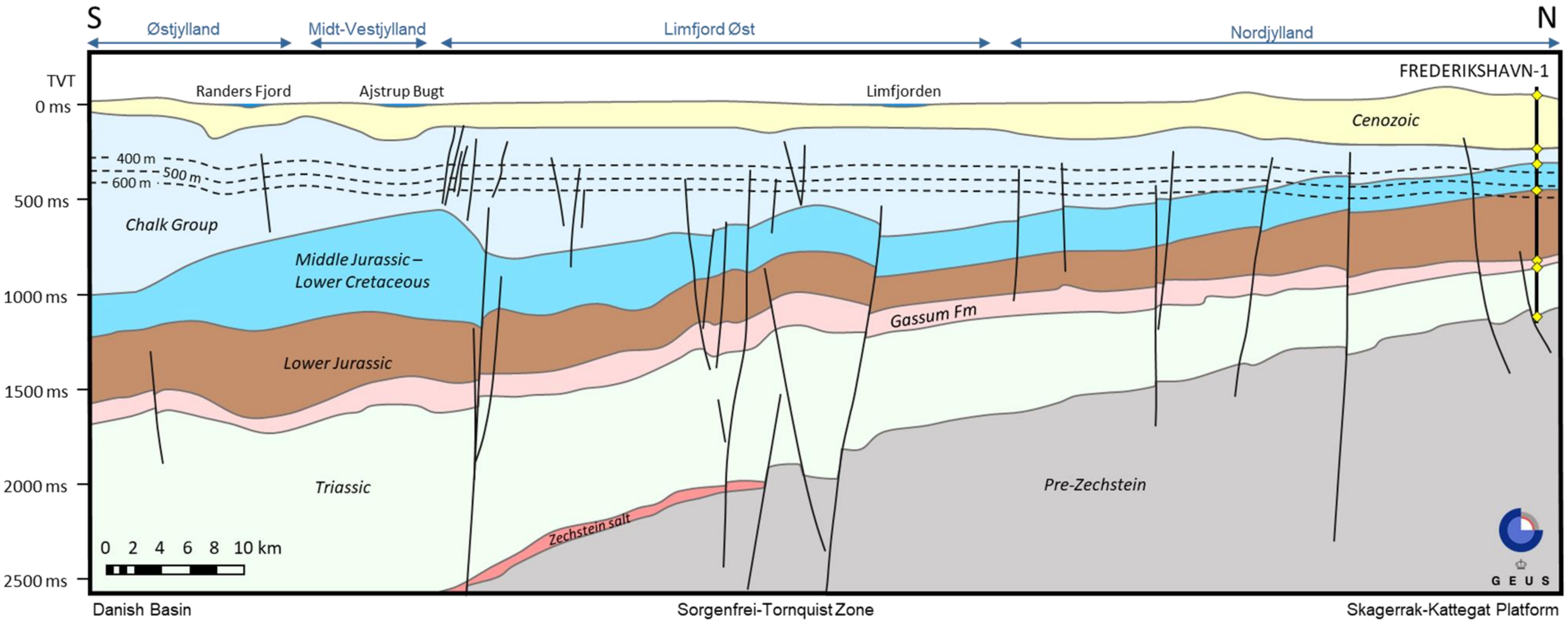


Figure 4.13 *Locations of the geological cross-sections are indicated with red lines on a structural map. The profiles are shown in Figures 4.14 – 4. 27. The Ringkøbing-Fyn High represents an area where basement rocks occur at relatively shallow depths (1–1.5 kilometers below surface) compared to the Danish Basin and the North German Basin where basement occurs at several kilometers' depth. Cross-section no. 14 from Scania is based on regional seismic data and represents an analogy to the geology of Bornholm (dotted line) where seismic data are absent.*



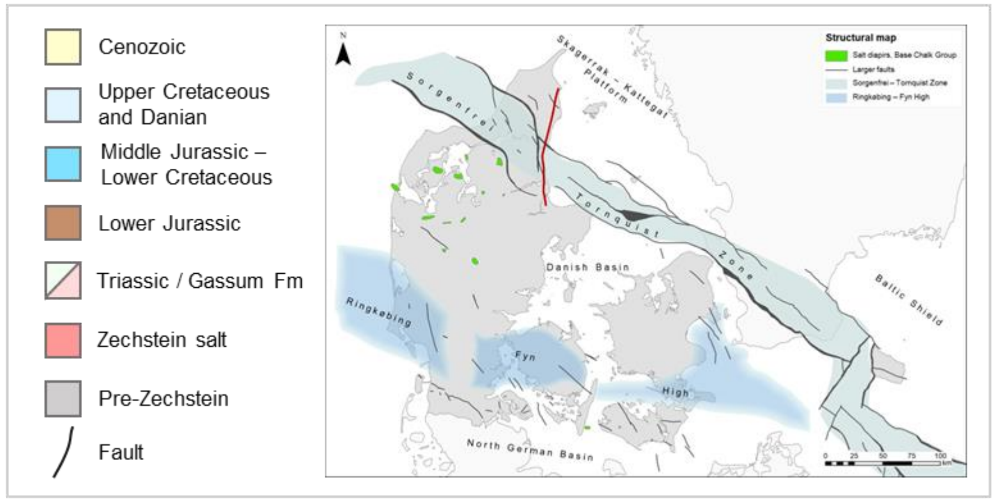


Figure 4.14. *Cross-section 1 extends from the Skagerrak-Kattegat Platform in the north across the Sorgenfrei-Tornquist Zone to the Danish Basin in the south, representing a length of approximately 100 kilometers.*

The Chalk Group constitutes most of the depth interval from near surface to more than 600 meters. Characteristic for the geological section is that the stratigraphic units dip towards the south. The Chalk Group has an overall wedge-shaped geometry due to uplift and associated erosion to the north. Thus, in the northernmost part of the cross-section, the Chalk Group thickness is approximately 100 meters (127 meters in the Frederikshavn-1 borehole), where only the lower part of the section is preserved. To the south it achieves thicknesses in the order of 1000 meters.

The thickness of the underlying Lower Cretaceous succession ranges from approximately 200 meters to several hundred meters, with greatest thicknesses to the south. To the north, around the Frederikshavn-1 borehole, the Lower Cretaceous section occurs at depths around 400 – 500 meters, but generally it occurs at depths exceeding 600 meters.

In the southern and central parts of the cross-section, the interval from 400 meters and upwards consists mainly of the Chalk Group which is succeeded by Cenozoic sediments. In the southern and central parts of the cross-section, the Cenozoic section is approximately 100 meters thick, while it is up to 300 meters thick in the Nordjylland area to the north.

Numerous faults are seen in the cross-section; some are deep seated while others occur only in the shallower sections. The distance between faults varies from a few kilometers to 10 kilometers. In the central part of the cross-section (Limfjord Øst), a complex system of faults extending from pre-Zechstein to Upper Cretaceous represents the Sorgenfrei-Tornquist Zone. Near Frederikshavn-1, a fault is seen to extend into the Cenozoic section indicating it has been active during the Cenozoic time. In parts of the Chalk Group, several minor, closely spaced faults occur above compression structures in the deeper sections. These faults are formed by stretching of chalk layers above the compression structures and may be associated with fracture systems.

Figure 4.14

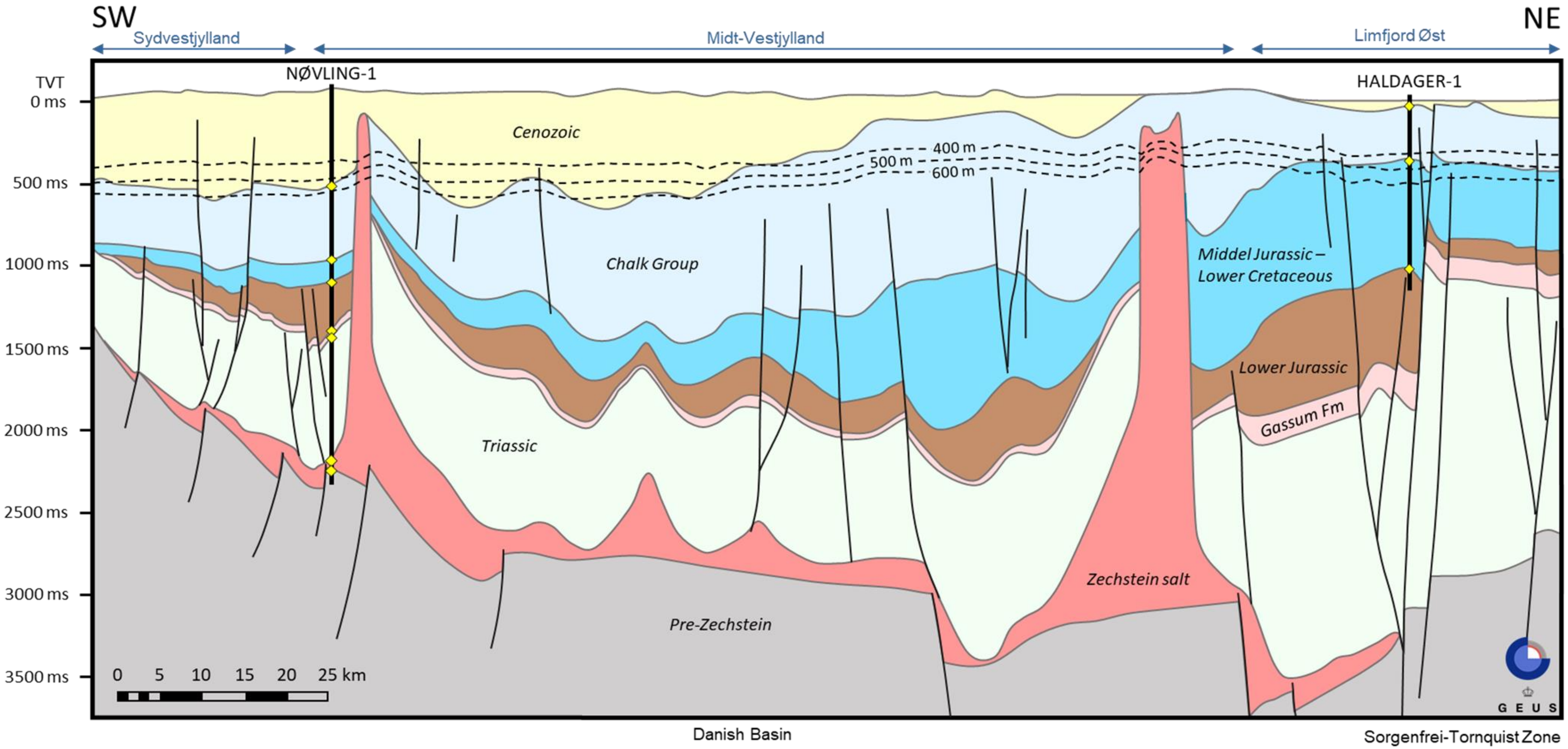


Figure 4.15. *Cross-section 2 extends from the Danish Basin in the southwest to the Sorgenfrei-Tornquist Zone in the northeast.*

The cross-section shows that the area is structurally complex due to the presence of numerous large faults and salt diapirs. The stratigraphic boundaries display varying dips and thicknesses within short distances, reflecting the different geotectonic regions. The southern margin of the Danish Basin is characterized by a northwards dipping Top Pre-Zechstein surface associated with increasing thickness of the Triassic to Upper Cretaceous stratigraphic interval in the central part of the basin towards the north.

In the southwest, Top Chalk Group occurs at 500 – 600 meters depth and is overlain by a thick succession of Cenozoic sediments. In the Limfjord Øst area to the north, Top Chalk Group occurs at or near surface and Base Chalk Group is at depths around 500 meters. The Middle Jurassic to Lower Cretaceous interval constitutes the depth interval from around 500 meters to 1000 meters or more.

Several deep faults extending from the Zechstein salt into the Chalk Group, and in some cases further into the Cenozoic section, occur at the southern basin margin, i.e., in Sydvestjylland and southwestern Midt-Vestjyllland. In the Midt-Vestjylland area, most deep faults terminate within the Chalk Group. Faults occurring in the Sorgenfrei-Tornquist Zone (Limfjord Øst) are relatively closely spaced, and some continue into the Chalk Group. One fault near the Haldager-1 borehole extends to the surface. The southern salt diapir penetrates the Chalk Group and terminates in the Cenozoic section at shallow depth.

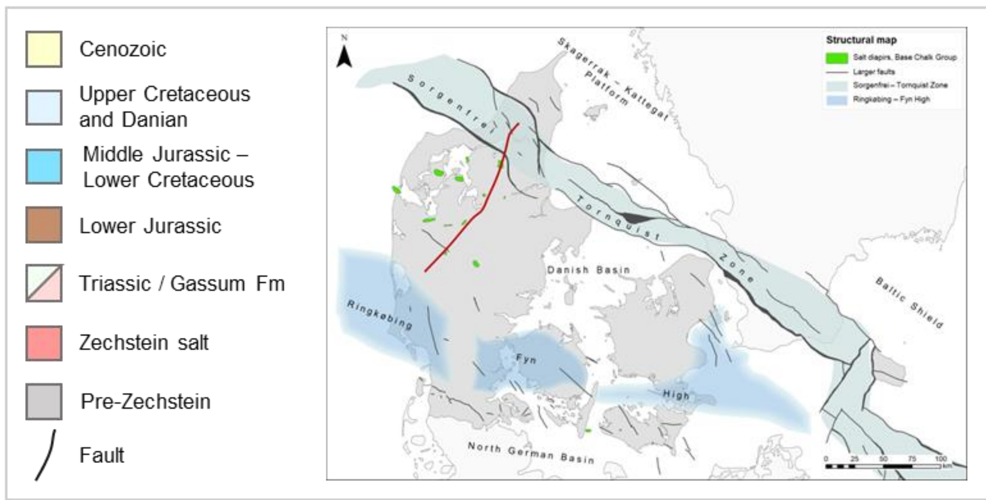


Figure 4.15

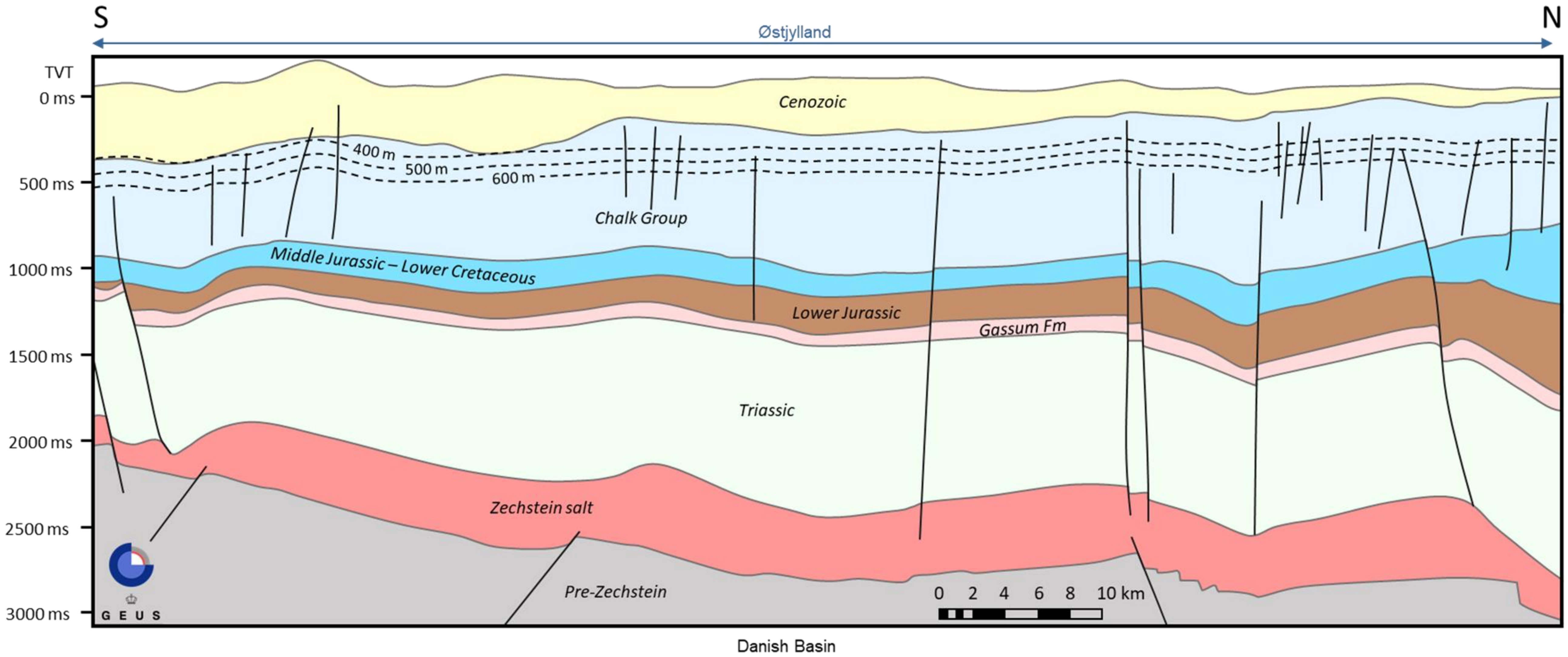
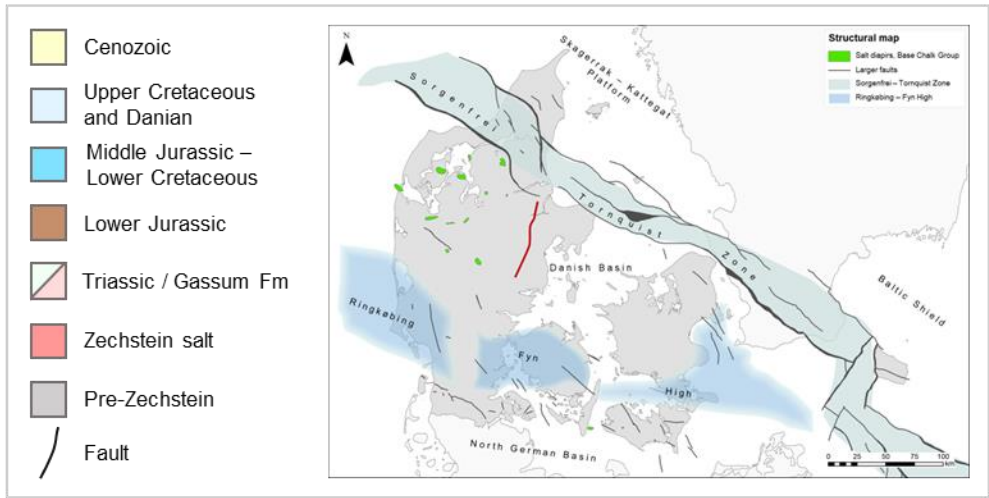


Figure 4.16. Cross-section 3 extends approximately 90 kilometers from south to north through the northern part of the Danish Basin.

The Cenozoic section varies in thickness from 400 meters in the south to 20 – 30 meters to the north where the Top Chalk Group occurs at or near surface. The base of the Chalk Group occurs at depths exceeding 600 meters along the entire cross-section.

Zechstein salt occurs widespread with varying thickness and gentle pillow structures have developed typically above major, deep-seated faults. The undulating topography of Top Zechstein salt is reflected in the overlying Triassic to Lower Cretaceous succession and, to a lesser extent, in the Chalk Group. Several large faults extend from the Zechstein salt into the upper part of the Chalk Group. Within the Chalk Group, closely spaced faults occur in areas where underlying salt pillows occur at great depths in the Zechstein section. Most of these minor faults terminate internally in the Chalk Group and show very little displacement, and they may be associated with locally generated extensional fractures which may be open or closed, depending on the local stress regime.



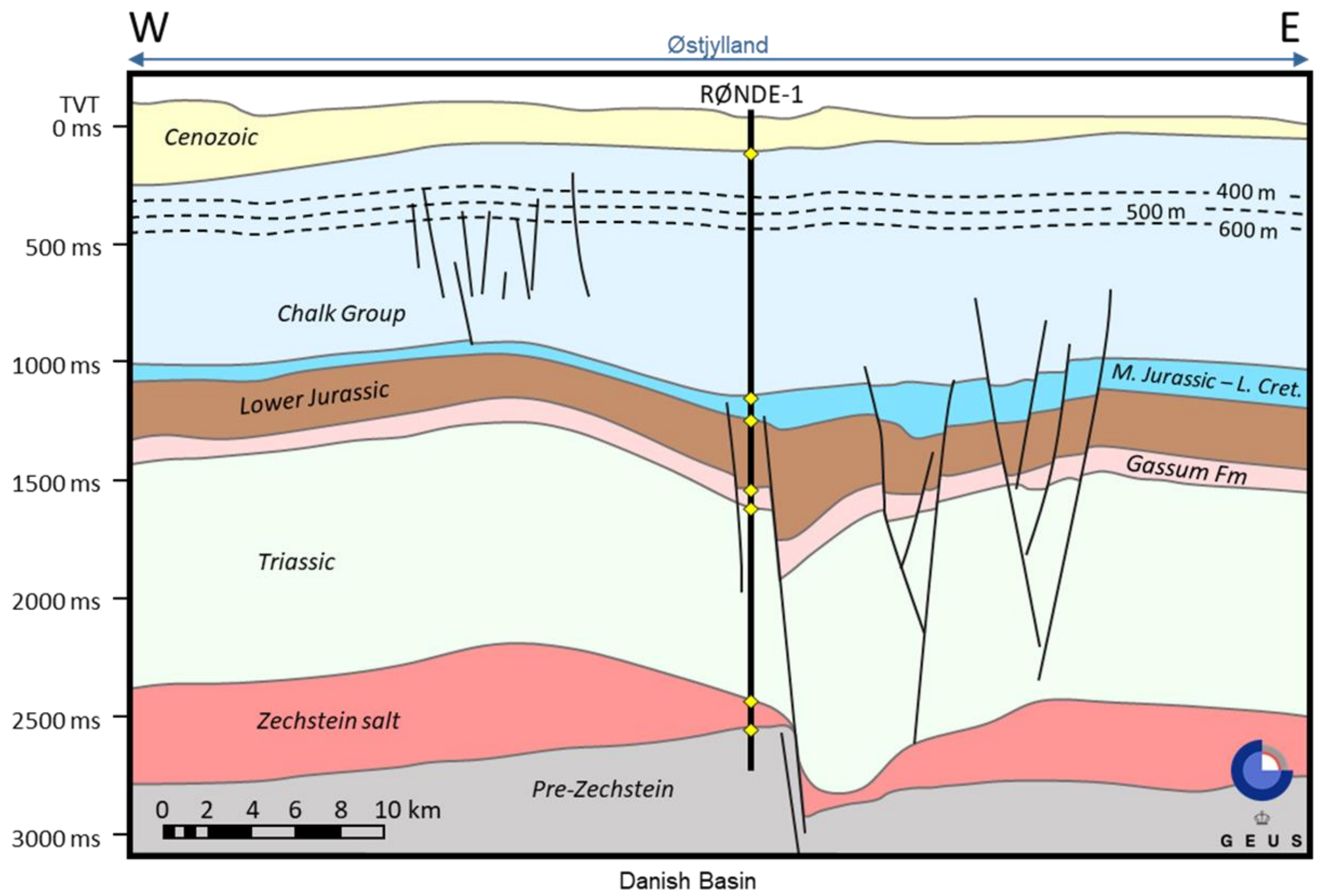
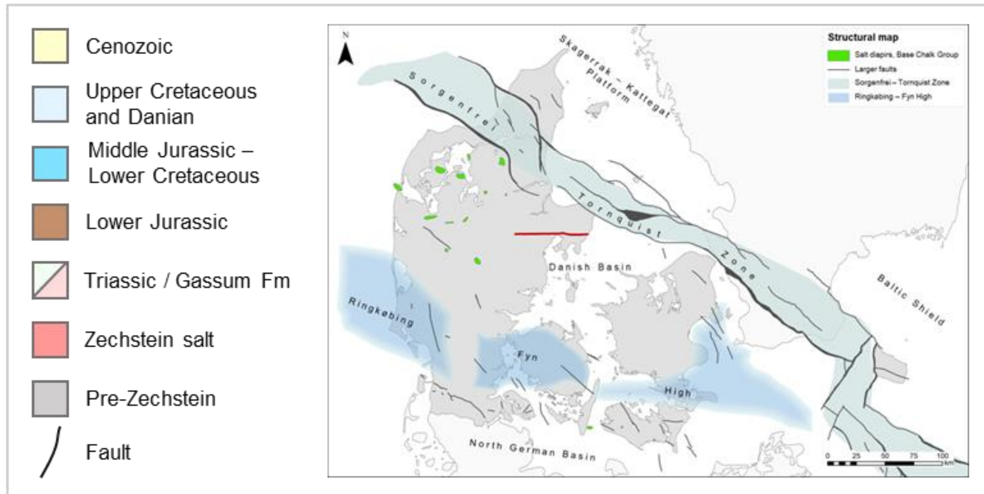
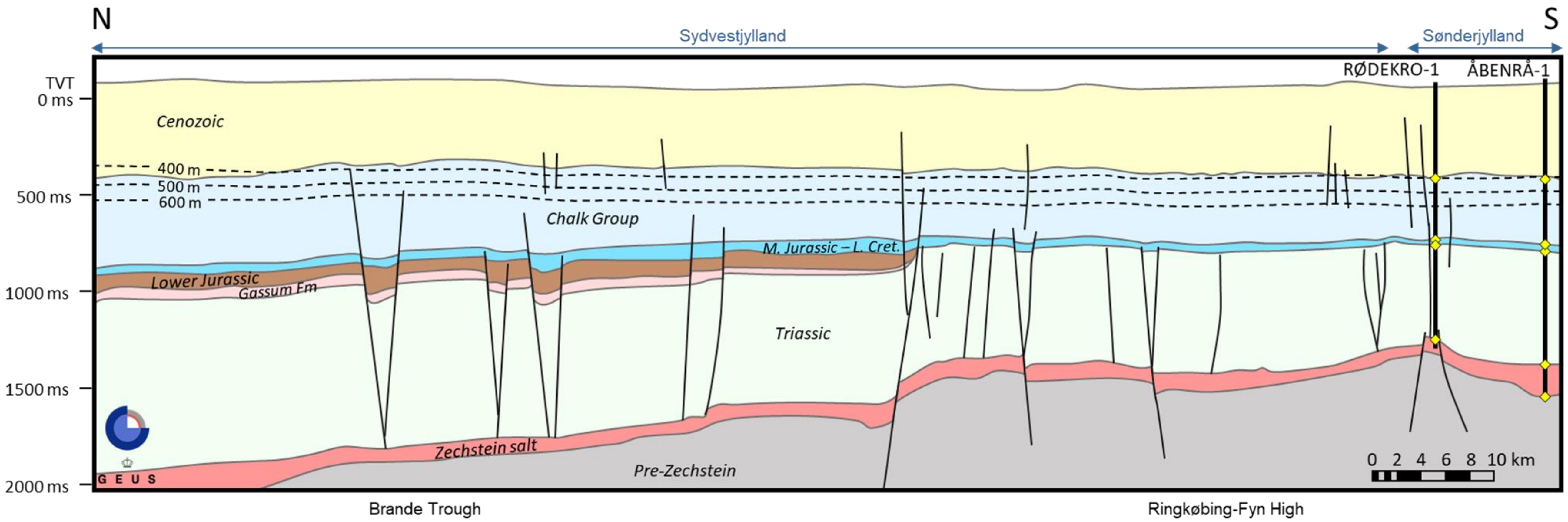


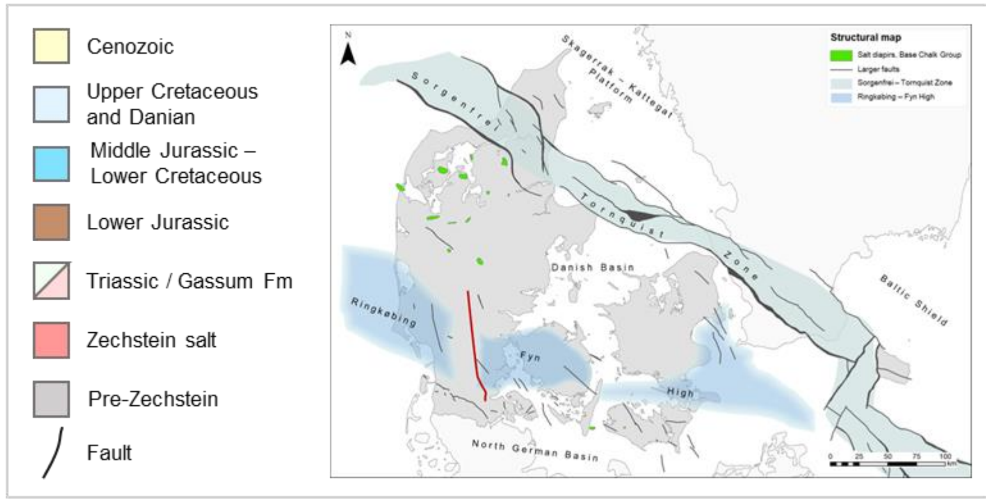
Figure 4.17. *Cross-section 4 illustrates an approximately 50 kilometer long, west – east oriented section through the Danish Basin.*

Along the entire length of the cross-section, chalk from the Chalk Group occurs in the 400 to 500 meters depth interval. The chalk section is relatively thick, and the base of the Chalk Group occurs well below 600 meters. The top of the Chalk Group occurs at depths around 100 meters (130 meters in the Rønde-1 well), with increasing depths towards the west (300 – 400 meters).

Several deep-seated faults extending from the Triassic into the lower part of the Chalk Group, occur east of the Rønde-1 well and are associated with salt withdrawal in the deeper Zechstein section. The geometry of gently dipping salt pillows in the Zechstein section is reflected in the shallower Triassic to Middle Jurassic – and Lower Cretaceous sections. A group of minor faults occurs within the Chalk Group above the western salt pillow. These faults formed as the result of extension due to salt movement and they may be associated with fracture systems.







Figur 4.18. *Cross-section 5 extends 120 kilometers from north to south from the southern part of the Danish Basin through the Brande Trough towards the margin of the North German Basin.*

The Chalk Group has a rather uniform distribution and thickness along the entire section with the top of the Chalk Group occurring at 400 meters depth and the base occurring at depths exceeding 600 meters. Likewise, the overlying Cenozoic section has a uniform thickness of around 400 meters. Sediments from the Lower Jurassic and Triassic (Gassum Formation) occur only in the Brande Trough in the northern part of the section at depths around 1000 ms.

Structurally, the upper 500 – 600 meters of the stratigraphy are relatively undisturbed. Some minor faults, extending from the upper part of the Chalk Group to the lower Cenozoic succession, occur with varying distance between them (2 - >10 km). Numerous faults occur in the deeper parts of the section from top Zechstein salt to the base Chalk interval. A few of these faults continue into the lower part of the Cenozoic section.

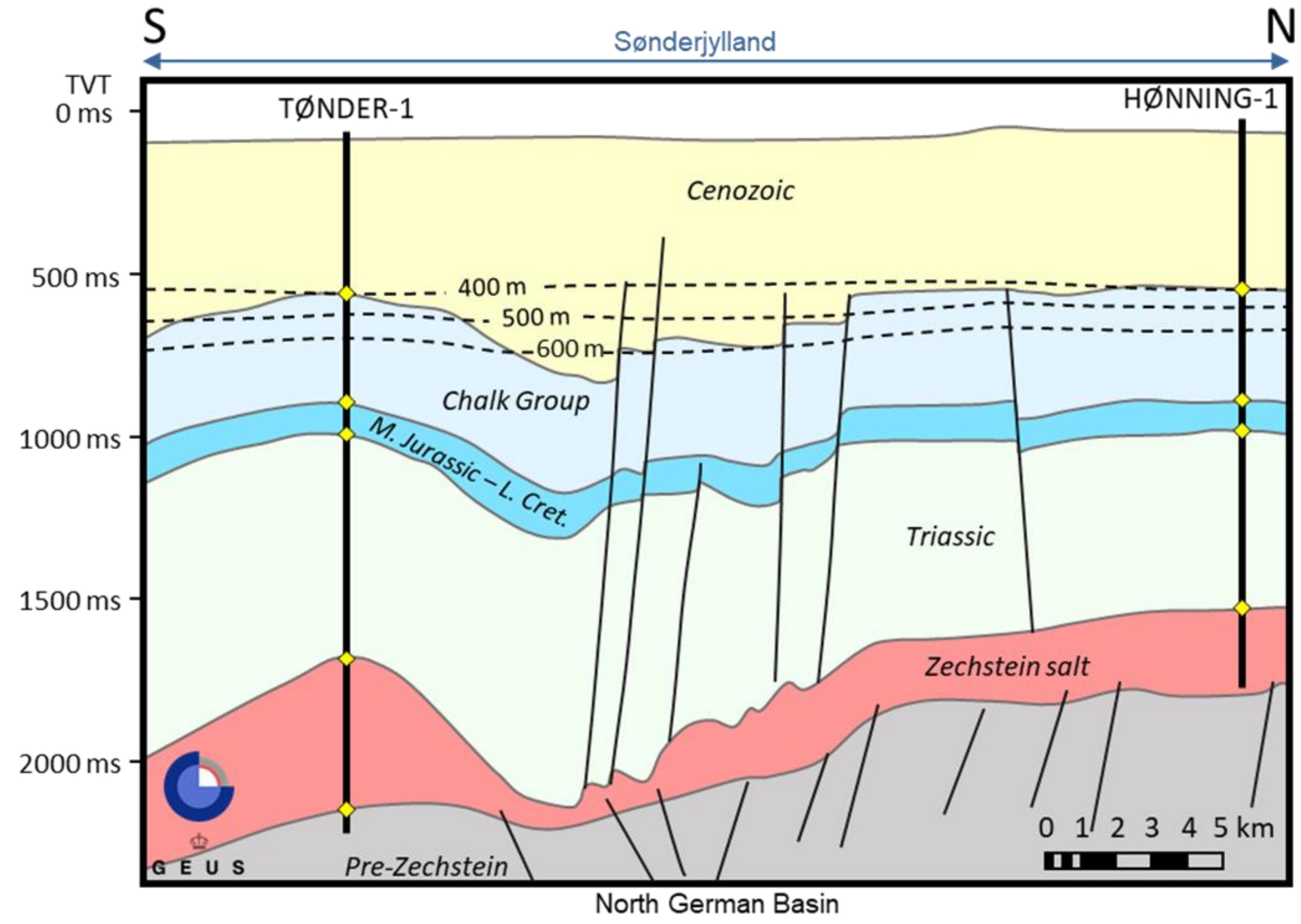
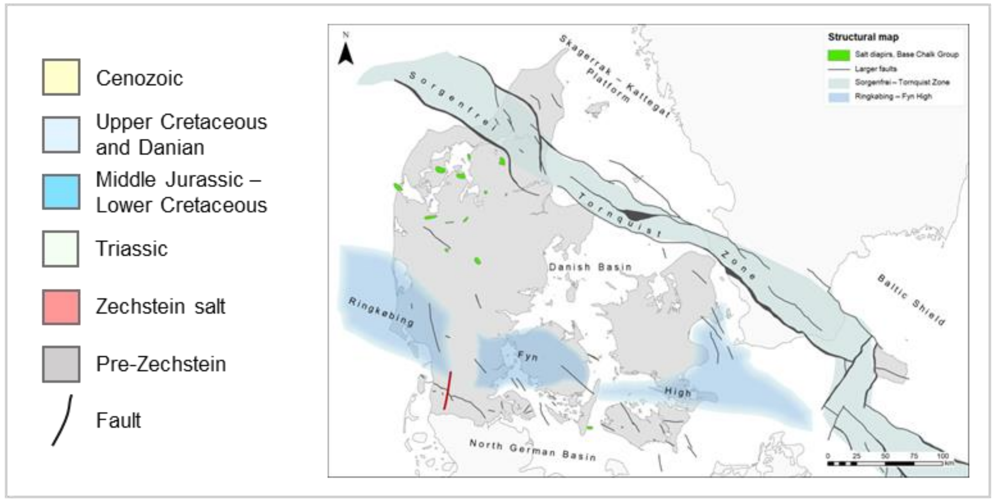
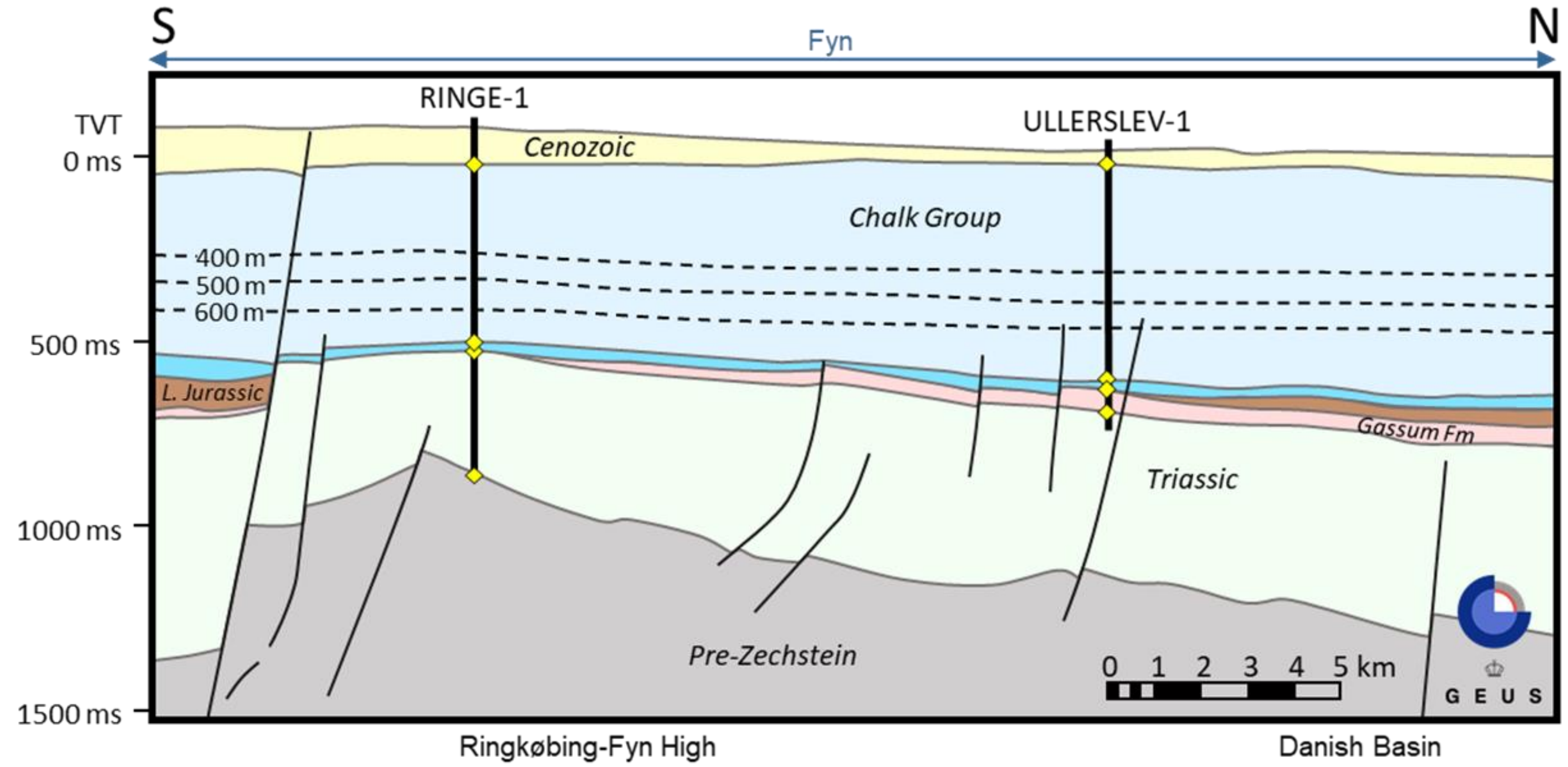


Figure 4.19. *Cross-section 6 illustrates an approximately 30 kilometer long, south – north oriented section of the northern margin of the North German Basin.*

The cross-section shows that Cenozoic sediments generally constitute the interval from surface to 400 – 500 meters depth, locally 600 meters, and the top of the Chalk Group therefore generally occurs deeper than 400 meters. The Chalk Group thickness is around 500 meters.

The Triassic, the Lower Cretaceous and the Upper Cretaceous/Chalk Group sections generally show uniform thicknesses across the area. Depth variations reflect the topography of the underlying top of the Zechstein salt, where salt remobilization has resulted in the formation of a salt ridge (drilled by the Tønder-1 well). On the northern side of the salt ridge, the salt is thin due to salt withdrawal into the salt ridge. This has caused subsidence of the overlying sections and the formation of faults, most of which extend from the base of the Triassic into the lower part of the Cenozoic section.





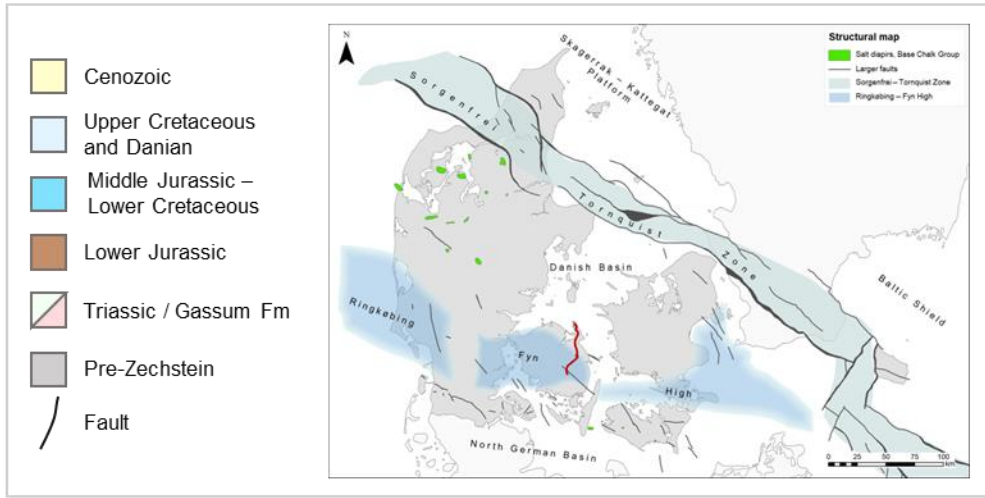


Figure 4.20. *Cross-section 7 illustrates an approximately 30 kilometer long, south – north oriented section across the Ringkøbing-Fyn High in the Fyn area.*

The top of the Chalk Group occurs at depths around 50 – 100 meters and the base of the Chalk Group is at depths exceeding 600 meters. The Chalk Group thickness increases slightly towards the north.

A large normal fault is present south of the Ringe-1 well and marks the southern boundary of the Ringkøbing-Fyn High. This fault extends from pre-Zechstein to ground level. It is associated with a large throw at Top Pre-Zechstein level and the Triassic to Lower Jurassic sections are displaced to greater depths towards the south. The Cenozoic section is slightly thicker south of the fault, indicating that the fault has been active recently during the Cenozoic time period and may potentially be reactivated.

Several normal faults occur in the deeper sections extending from the pre-Zechstein at great depths into the lowermost part of the Chalk Group.

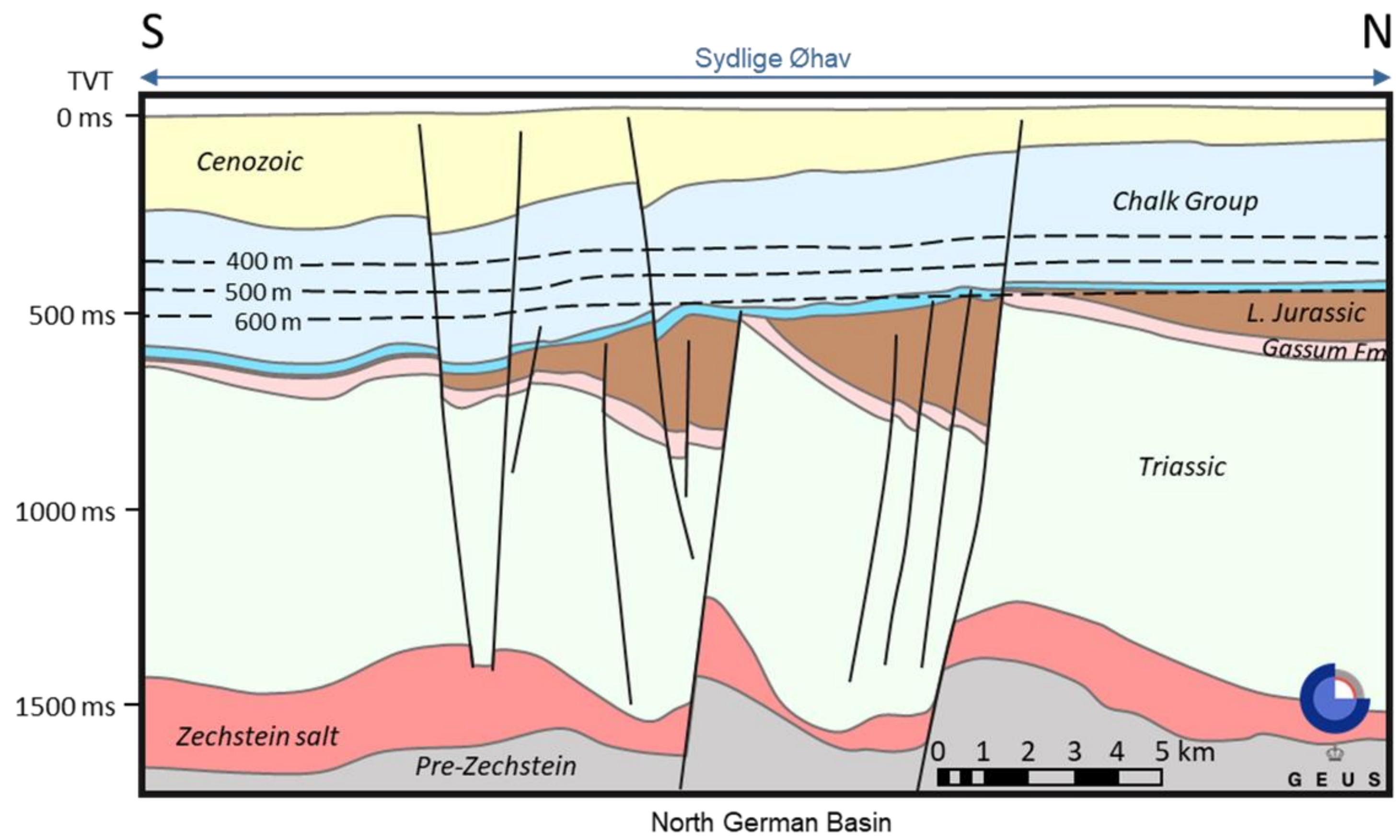
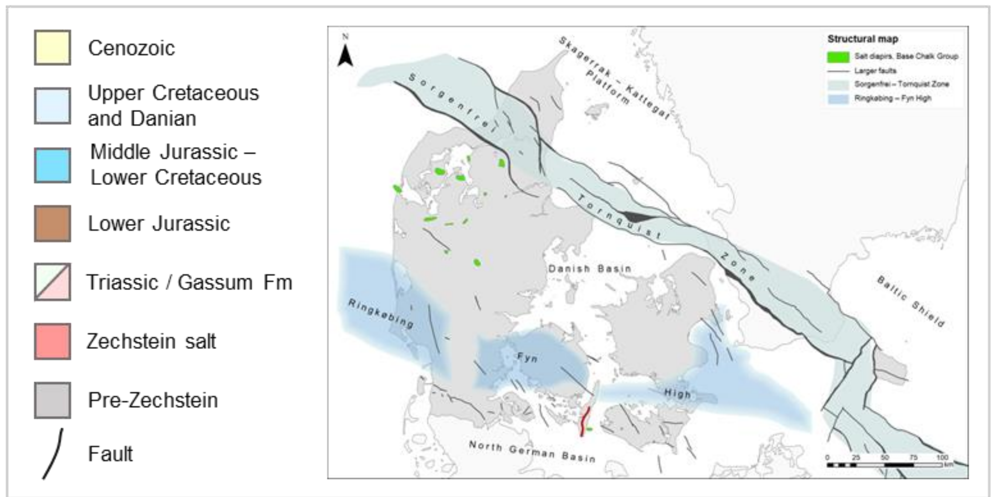


Figure 4.21. *Cross-section 8 presents an approximately 30 kilometer, south – north oriented section from the northern margin of the North German Basin towards the Ringkøbing – Fyn High.*



The Cretaceous sections have relatively uniform thicknesses along the entire profile, the Chalk Group being by far the thickest. The base of the Lower Cretaceous represents a major unconformity as the Lower Cretaceous section rests varyingly on Triassic and Lower Jurassic sediments.

Along the entire profile, the Chalk Group occurs in the 400 – 500 meters depth interval. The top of the Chalk Group occurs at 100 meters depth in the northern part of the profile increasing to 300 meters in the southern part. The Lower Cretaceous interval is very thin (near the limit of seismic resolution) and occurs generally deeper than 600 meters, except for in the northernmost part of the profile where it locally occurs at depths between 500 and 600 meters. Lower Jurassic sediments are found at 600 meters or deeper.

Deep-seated faults extend from the pre-Zechstein to shallow depths near surface. These faults form the boundaries of small half-grabens. The thickness of the Lower Jurassic section varies from zero to several hundred meters over short distances and is controlled by a complex interaction between the geometry of the fault-bounded half-grabens and remobilized Zechstein salt in the underlying section.

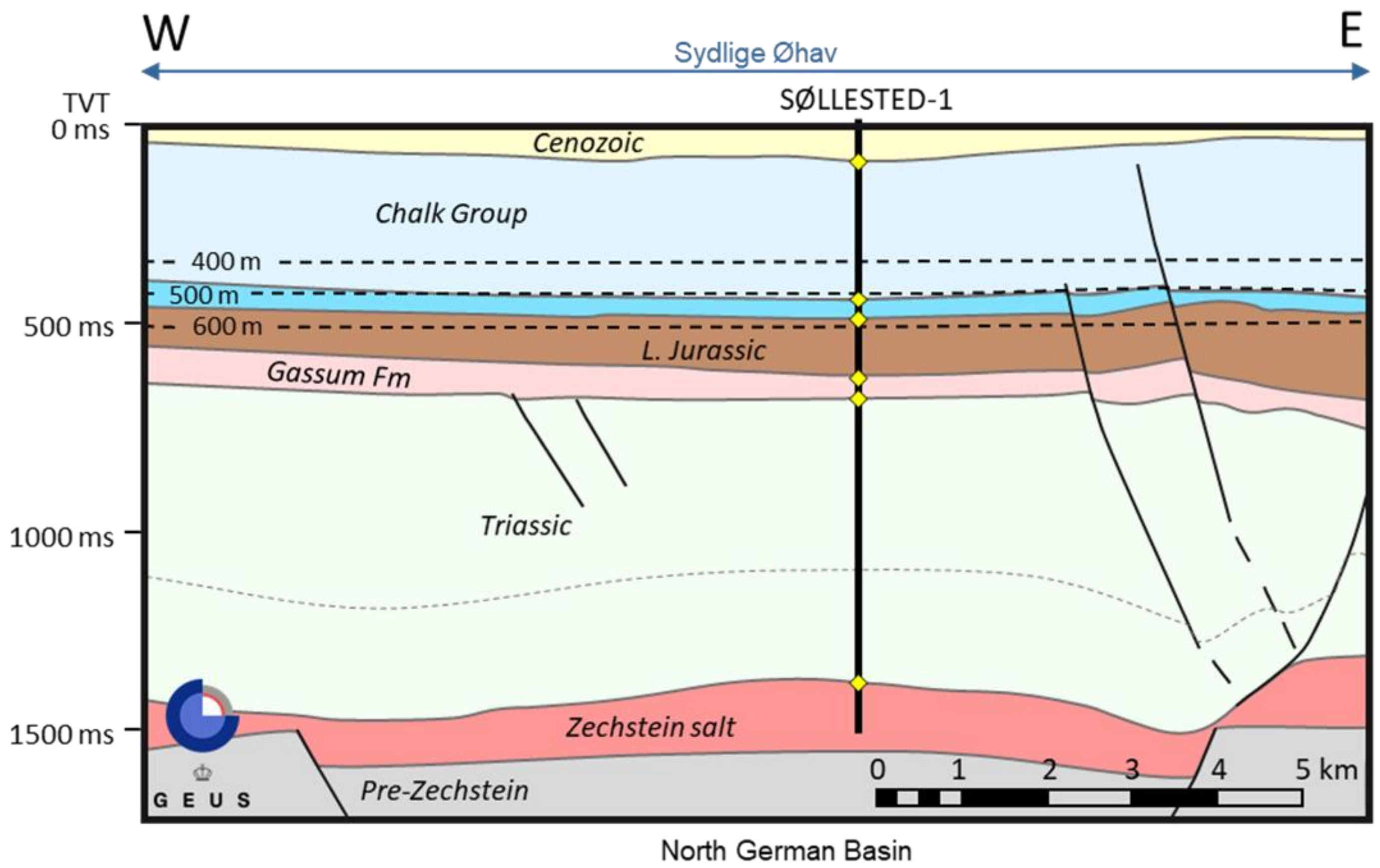


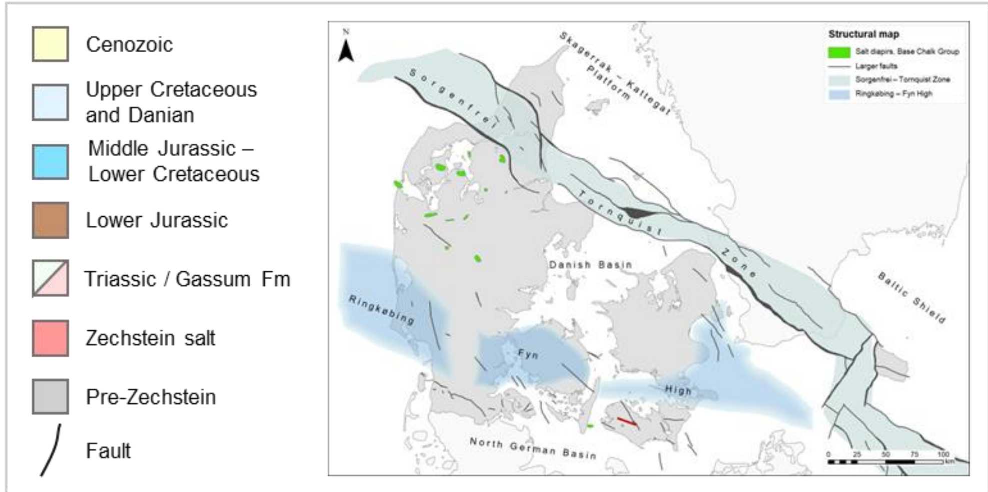
Figure 4.22. *Cross-section 9 illustrates an approximately 15 kilometer long, west to east oriented section along the northern margin of the North German Basin.*

Characteristic for this section is the uniform thicknesses of the stratigraphic intervals from the Triassic Gassum Formation to the Cenozoic section.

The top of the Chalk Group occurs at depths shallower than 100 meters below surface. The Chalk Group thickness is around 450 meters, and the base occurs at approximately 500 meters depth. The Cenozoic section is 86 meters thick in the Søllested-1 well drilled in the thickest part of the section. Top Lower Cretaceous occurs at approximately 500 meters depth and the Lower Cretaceous section is laterally continuous and generally around 50 meters thick. The Jurassic section varies in thickness from around 100 meters in the west to several hundred meters to the east. Thus, sediments from the Lower Cretaceous as well as from the Jurassic section constitute the sedimentary rocks in the 500 – 600 meters depth interval.

It is important to notice that the laterally continuous Gassum Formation to Chalk Group sections, displayed as being without significant depth or thickness changes across the 15 kilometer long section, may be expected to display significant variations over short distances in the north – south direction due to the presence of small, tilted half grabens as illustrated in Figure 2.21.

Two deep faults related to salt remobilisation occur in the eastern part of the section with the easternmost fault extending into the uppermost part of the Chalk Group.



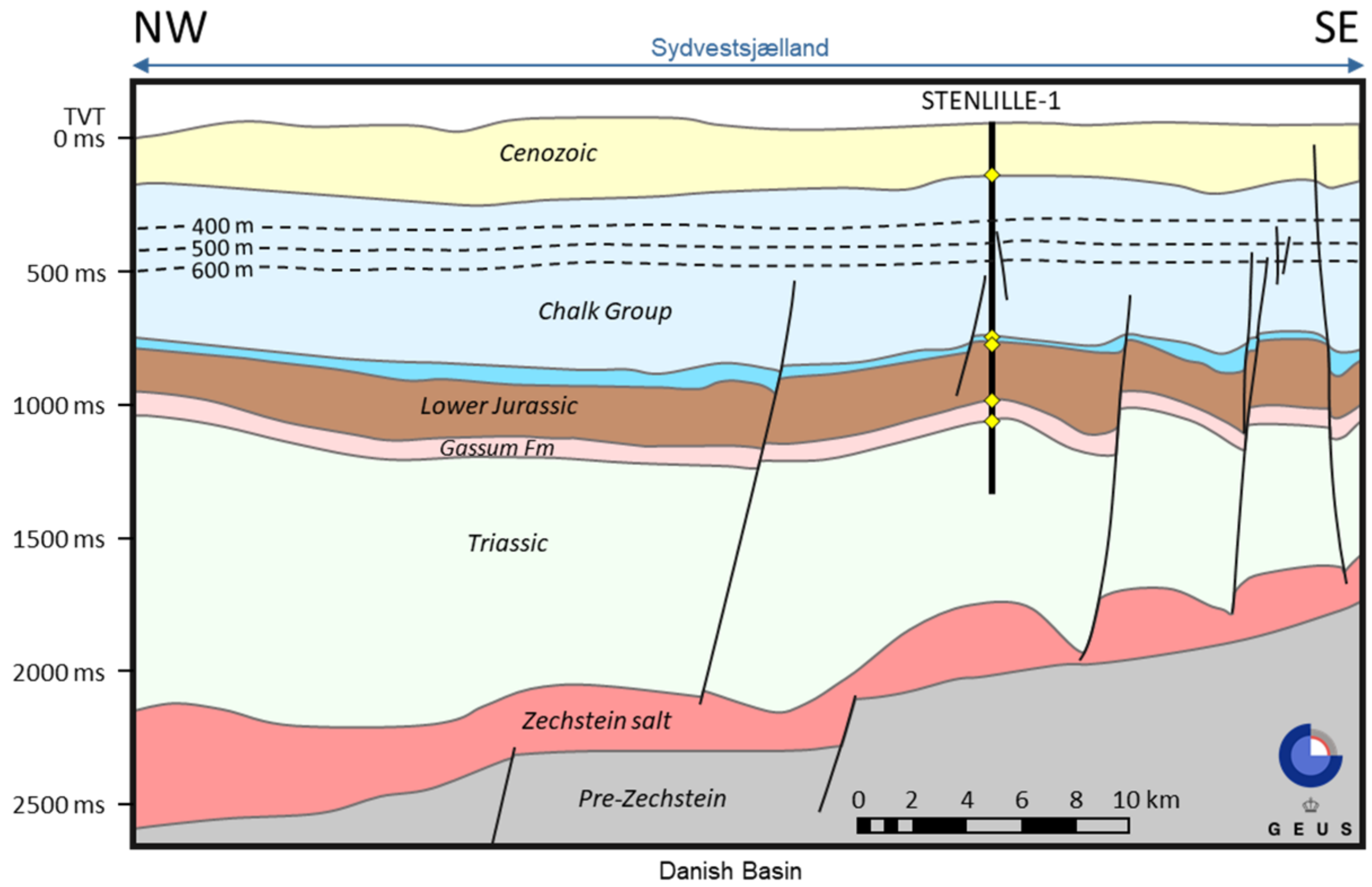
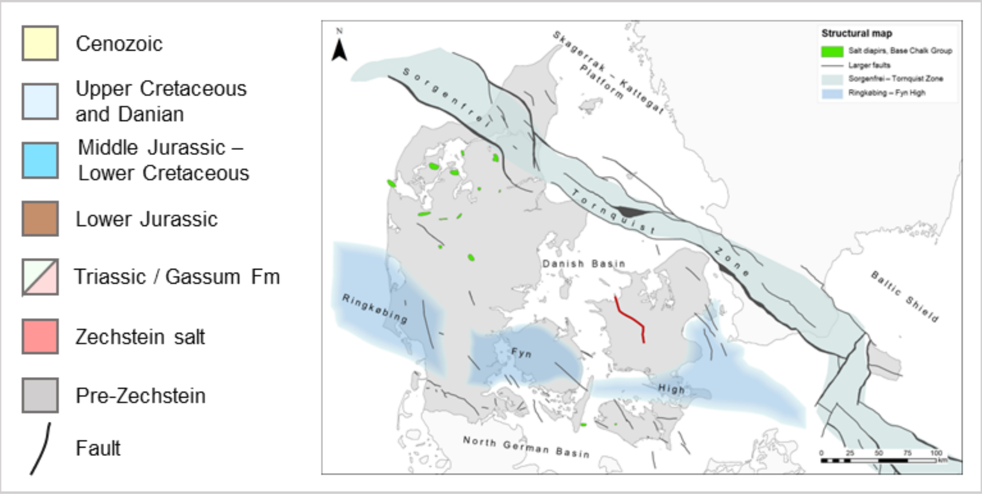


Figure 4.23. Profile 10 illustrates a 45 kilometer long northwest – southeast trending geological cross-section from the eastern part of the Danish Basin.

Characteristic for this profile is that the Chalk Group has a uniform thickness of around 1000 meters (1008 meters in the Stenlille-1 well), and it is overlain by 200 – 300 meters of Cenozoic sediments. Below the Chalk Group is a thin section of Lower Cretaceous sediments and a thicker section of Lower Jurassic sediments.

Several faults, extending from the Zechstein salt into the lower part of the Chalk Group, are seen in the southeastern part of the profile. They are clearly related to remobilization of salt, which has resulted in displacement of the overlying sections. One fault continues into the Cenozoic section to a depth near terrain, indicating that fault movements occurred in the late Cenozoic.



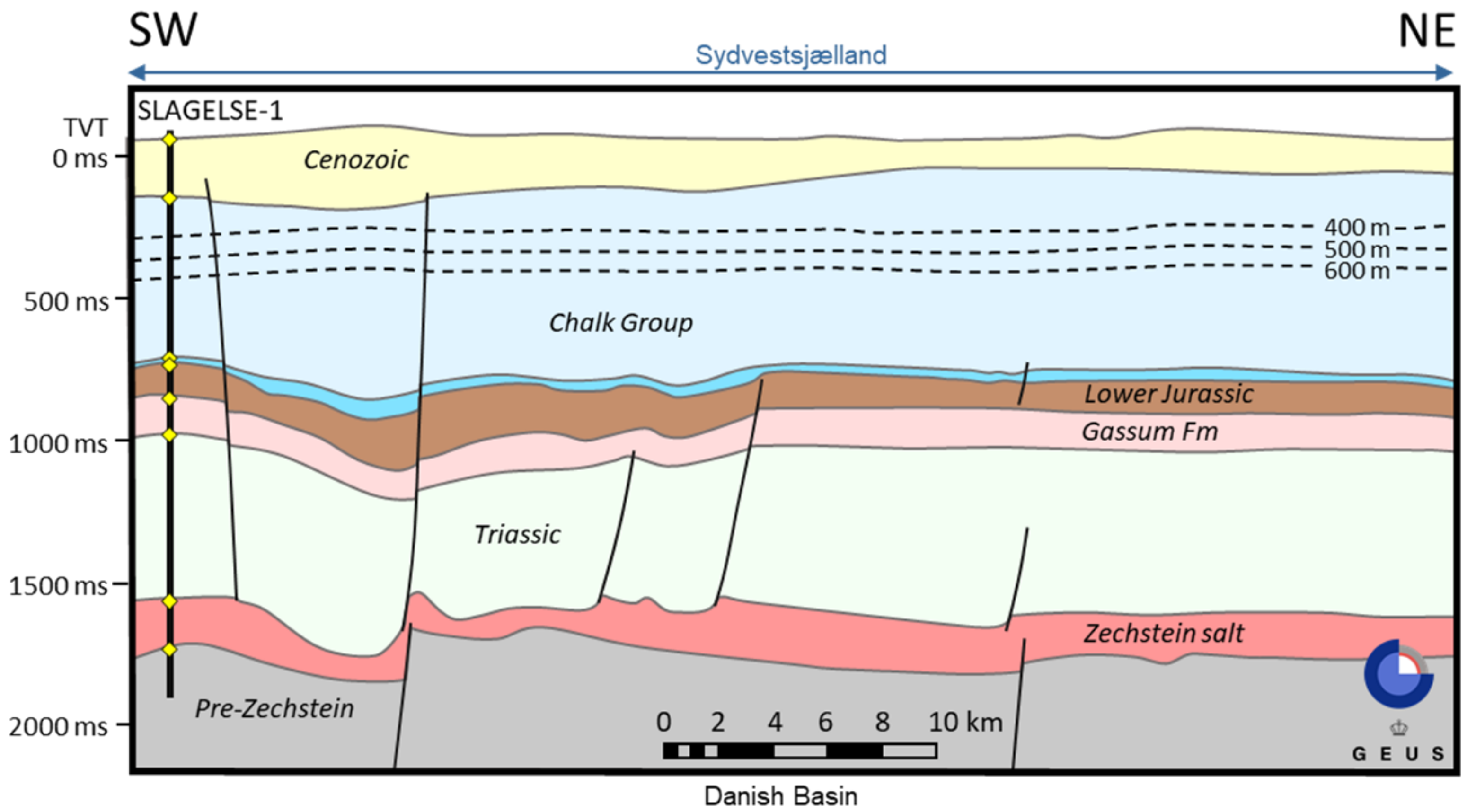
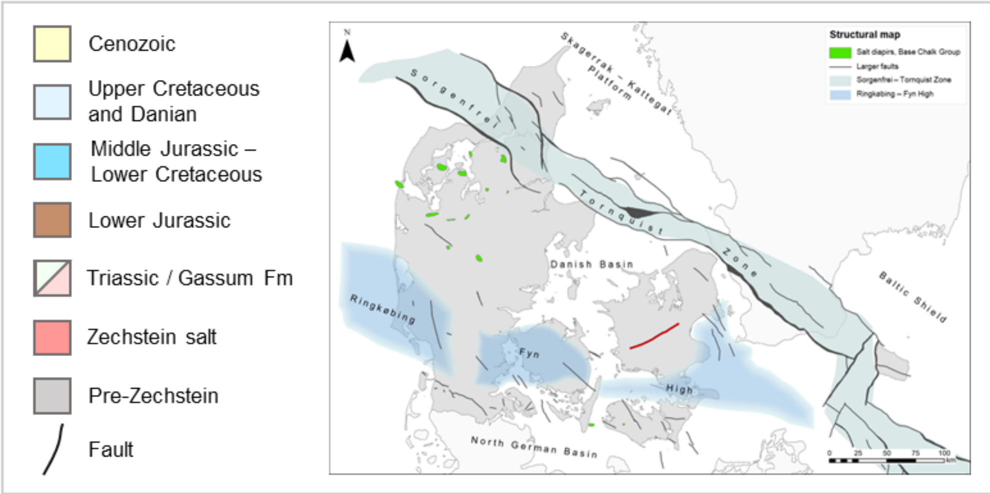


__Figure 4.24.__ Profile 11 illustrates an approximately 50 kilometer long, southwest – northeast oriented geological cross-section through the eastern part of the Danish Basin.

Characteristic for the cross-section is the relatively uniform thicknesses and undisturbed sections of the Triassic to Cenozoic. The Chalk Group is around 1000 meters thick. The top of the Chalk Group occurs generally at 200 – 300 meters depth with the greatest depth near the Slagelse-1 well. Below the Chalk Group, there is a thin Lower Cretaceous section and a thicker section of Lower Jurassic sediments.

Along the entire length of the profile, the depth interval from 400 meters to 500 meters consists of chalk from the Chalk Group, and the base of the chalk sediments occurs several hundred meters deeper. The uppermost 200 – 300 meters of the section consists of Cenozoic sediments.

Two large faults extend from the Zechstein salt into the Cenozoic section where a small displacement is observed across the faults indicating that the faults have been active during the Cenozoic.



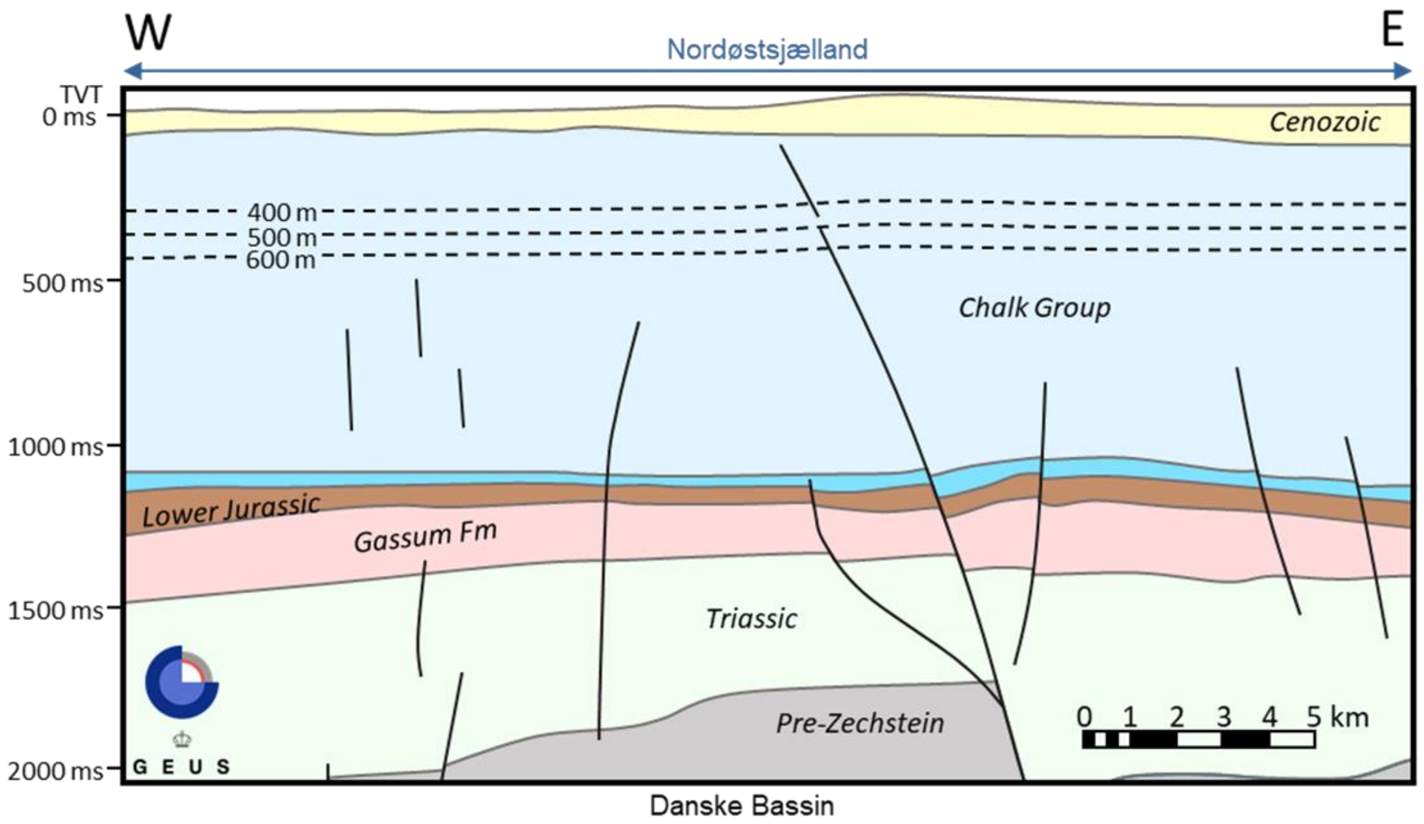
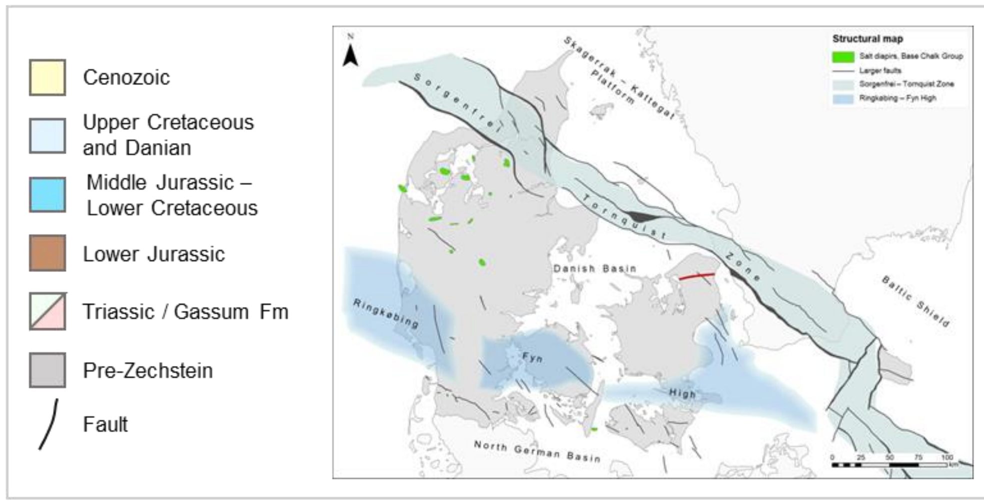


__Figure 4.25.__ Profile 12 illustrates an approximately 25 kilometer long, west – east oriented cross-section from the northeastern margin of the Danish Basin.

Characteristic for this profile is the lateral continuity and uniform thickness of the sections from the Triassic Gassum Formation to the Cenozoic. The Top Chalk surface occurs at depths from 50 meters to 150 meters and the base is deeper than 1000 meters, thus chalk sediments constitute the dept interval from 400 to 500 meters.

Several faults occur in the deeper part of the cross-section extending from the Triassic sediments into the Chalk Group, but with very small or no visible off-sets. A large, branched fault intersects the entire succession from pre-Zechstein to shallow depths near terrain and, therefore, it is possible that the fault has been active recently. The fault plane becomes less steep in an upwards direction suggesting that this fault is a transverse fault associated with lateral displacement rather than vertical displacement.



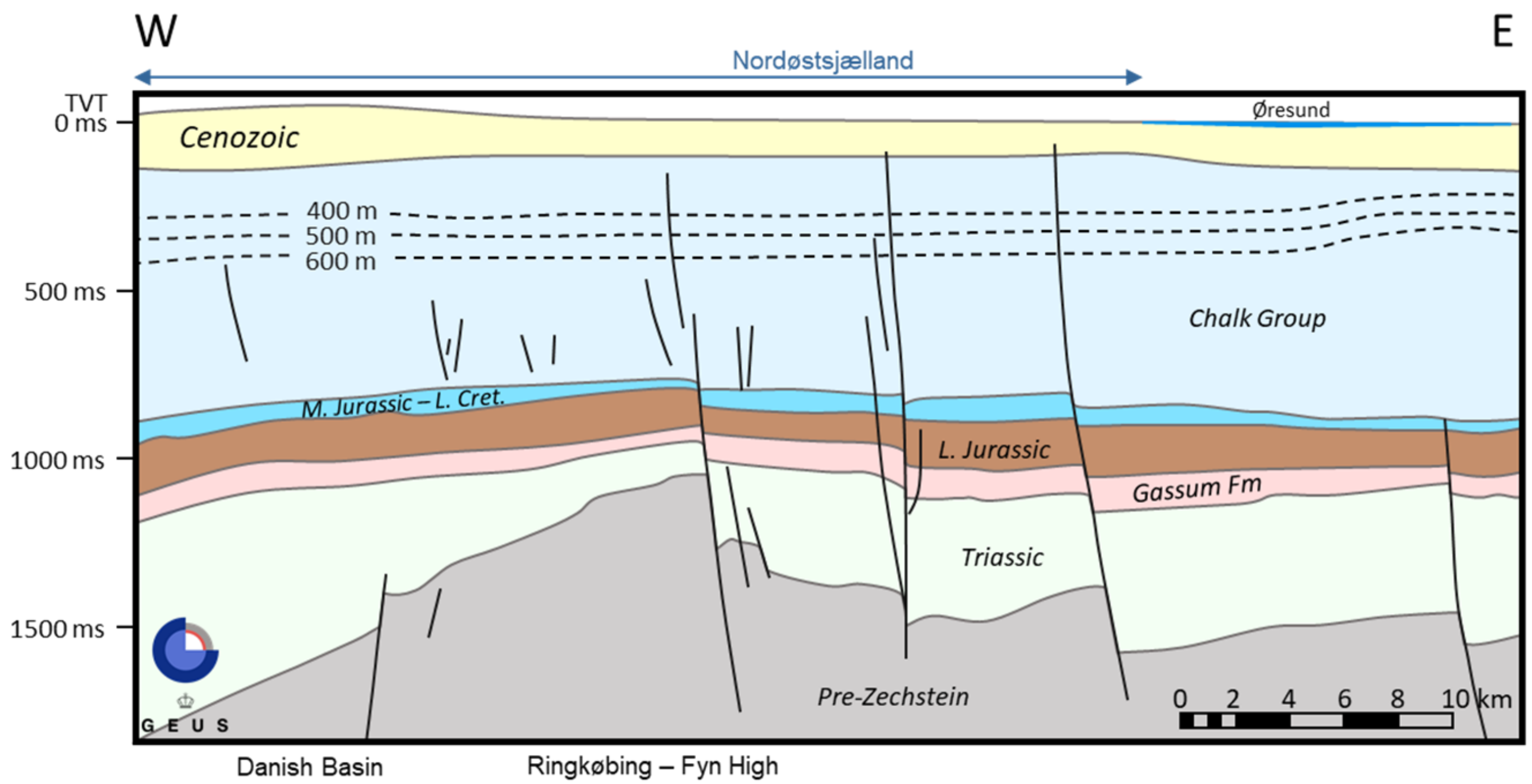
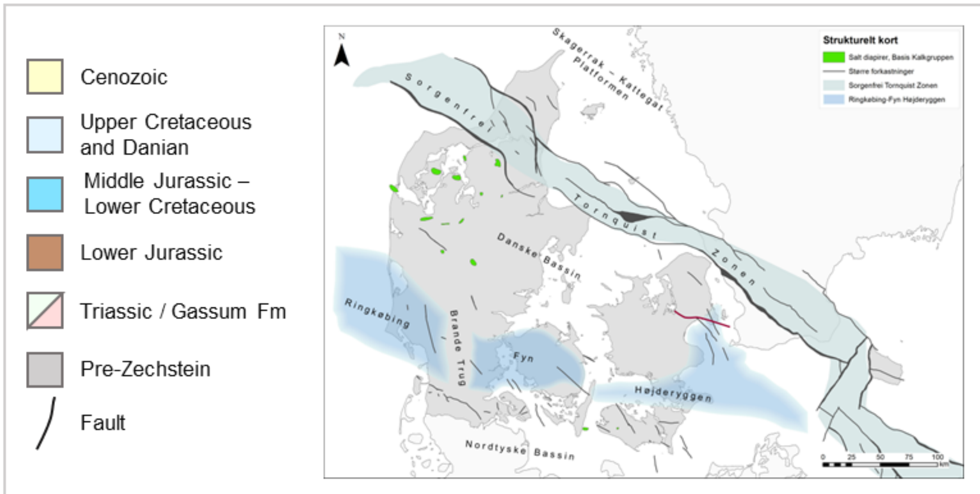


Figure 4.26. Profile 13 illustrates a west to east oriented cross-section extending from the easternmost part of the Danish Basin across the northernmost part of the Ringkøbing-Fyn High.

Characteristic for this section is that the top of the Chalk Group occurs at depths from 100 to 200 meters and the Chalk Group has a relatively uniform thickness exceeding 1000 meters. Thus, along the entire cross-section chalk sediments constitute the depth interval from 400 to 500 meters.

In the central part of the profile, across the Ringkøbing-Fyn High, three major faults intersect the entire section from pre-Zechstein to the base of the Cenozoic indicating that they have been active during the Cenozoic. Significant off-sets occur in the deeper pre-Zechstein and Triassic sections, whereas very small off-sets are mapped at base and top of the Chalk Group. The middle fault branches off into a 2 – 3 kilometer wide system of several minor faults. This fault geometry is typical of transverse faults with lateral displacement. Several minor faults occur internally in the Chalk Group but with limited or no vertical displacement.



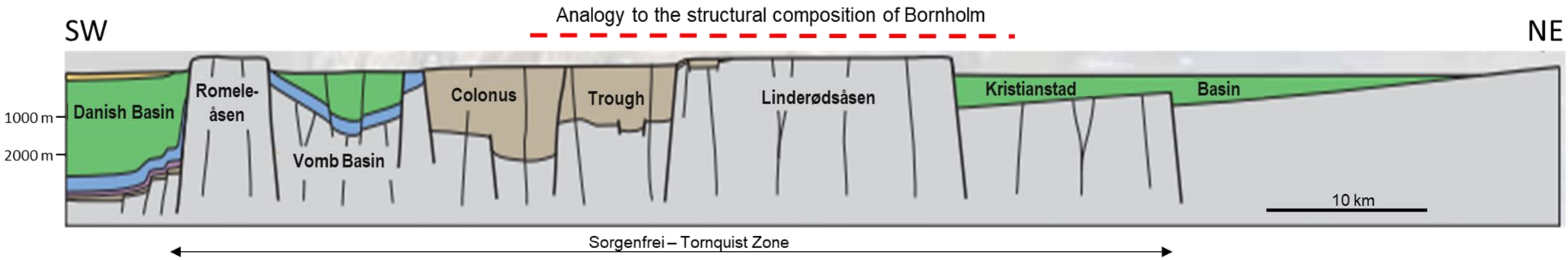
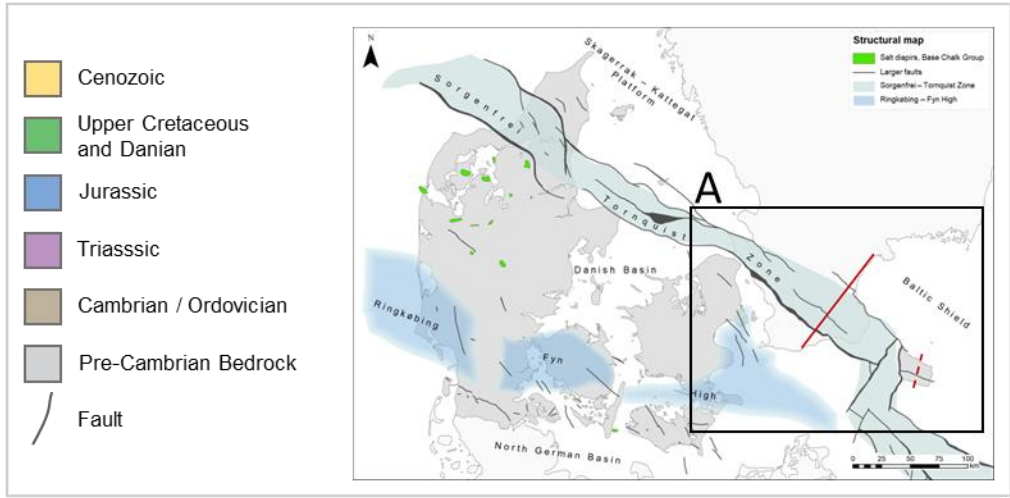


Figure 4.27. Profile 14 shows a southwest – northeast oriented cross-section across the Sorgenfrei – Tornquist Zone in southern Skåne, as presented by Graversen and Holm (2011). It illustrates the structural framework resulting from the tectonic movements that have taken place in and around the Sorgenfrei – Tornquist Zone in the southwestern Baltic Sea area. Therefore, it can be used as an analogy to the geological and structural conditions on Bornholm, which have not been mapped seismically.

Along the profile, bedrock (grey signature) continues to great depths (much deeper than 2000 meters). Sedimentary deposits (coloured signatures) occur in minor grabens and half-grabens overlying the bedrock.

Structurally, the profile is characterized by fault blocks that are displaced upwards and downwards creating a series of horsts and troughs. Linderødsåsen in the middle of the profile is an uplifted horst consisting entirely of bed rock, while the Colonus Trough immediately to the southwest is a graben structure filled with a thick section of sedimentary deposits. Since Bornholm is located in the Sorgenfrei – Tornquist Zone close to the Skåne area, it has the same tectonic history and a similar structural framework as illustrated in map A (Graversen & Holm, 2011). Thus, Bornholm is composed by a northern horst block of bedrock, and a southern trough comprising several smaller fault blocks, where sedimentary rocks of highly varying age, lithology and thicknesses overlie the bedrock.



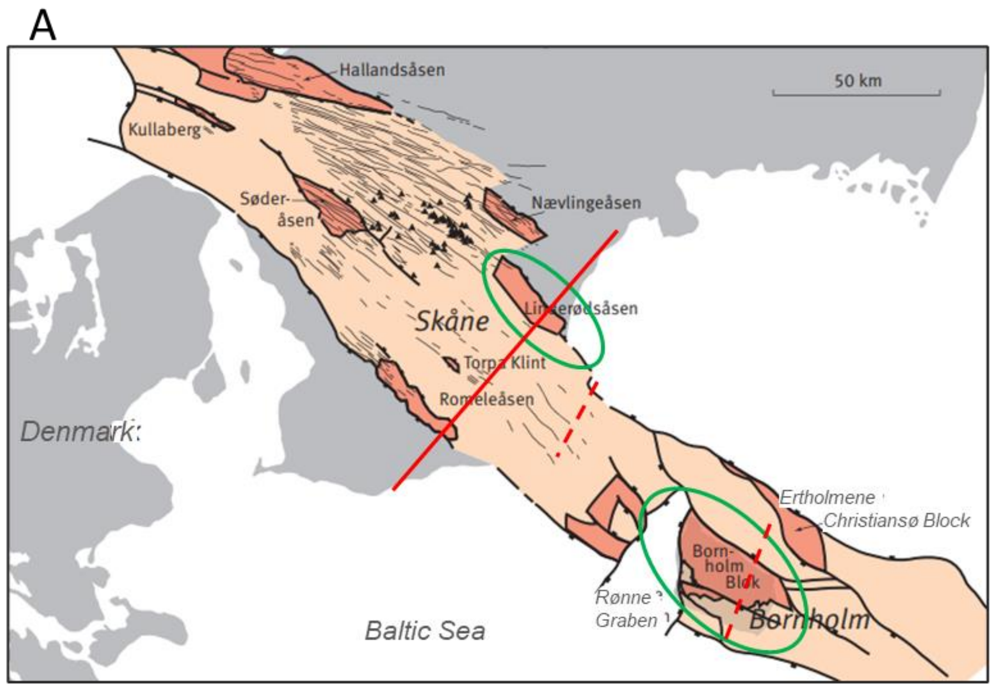


Figure 4.27

4.4 Geological areas

Eleven geological areas have been outlined as shown with coloured polygons in Figure 4.28, where major cities and community boundaries are also indicated. Only the onshore areas within the polygons are of interest for potential radioactive waste disposal. In Figure 4.29 the location of geological cross-sections, which illustrate the geology of the different areas is shown. The extent of the areas is indicated above the cross-sections (shown in Figure 4.14–4.27) and the structural elements are indicated below the cross-sections and on the inserted structural overview maps. The cross-sections illustrate the typical geological record, and the structural framework and complexity in the areas. Overview maps of depth and thicknesses of the geological units are shown in Figures 4.4–4.12. Detailed depth and thickness maps are presented for each area in Chapter 6.

The area outlines and the epicenters of registered earthquakes are indicated on the structural map shown in Figure 4.30. In areas where seismic activity is registered, and major faults are mapped to extend to near surface positions it is likely that future fault re-activation will be associated with earthquakes. Therefore, it is important to characterize faults from seismic data and map their extension both vertically and laterally to avoid disposal in sites with risk of seismic activity.

The geological characteristics that have been used to distinguish the different areas are described briefly in the following sections.

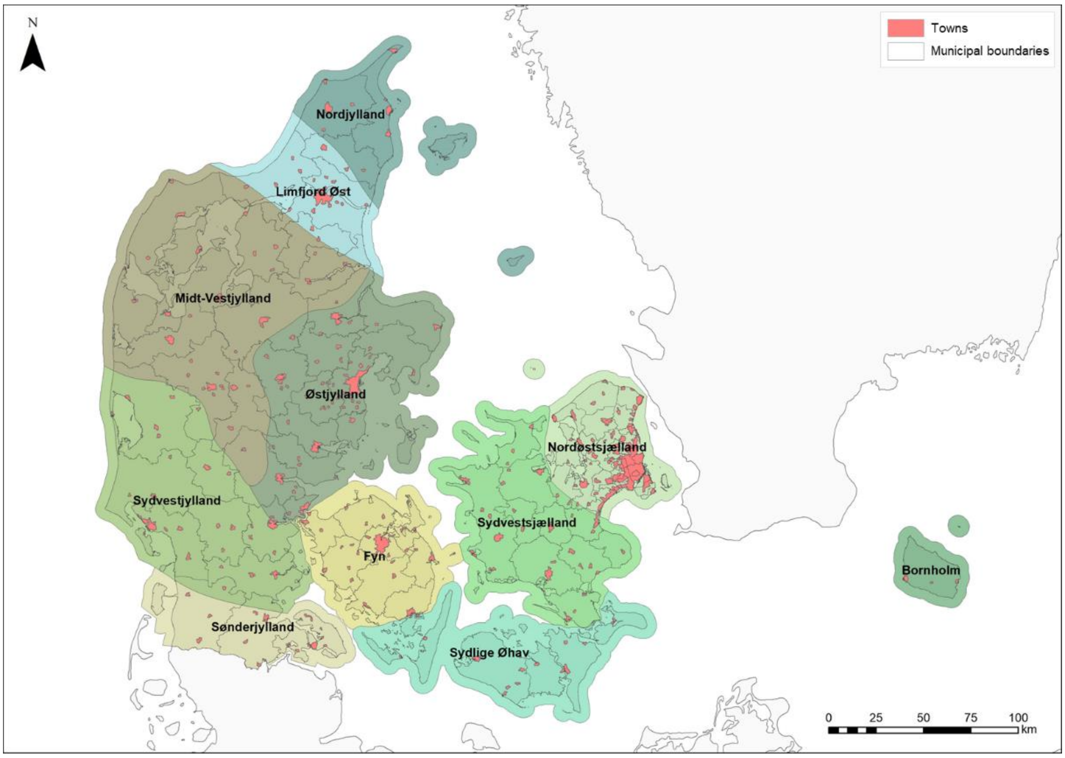


Figure 4.28. *Map showing outlines of the geological areas with different colours, major cities, and community boundaries. Detailed maps for each area are presented in Chapter 6.*

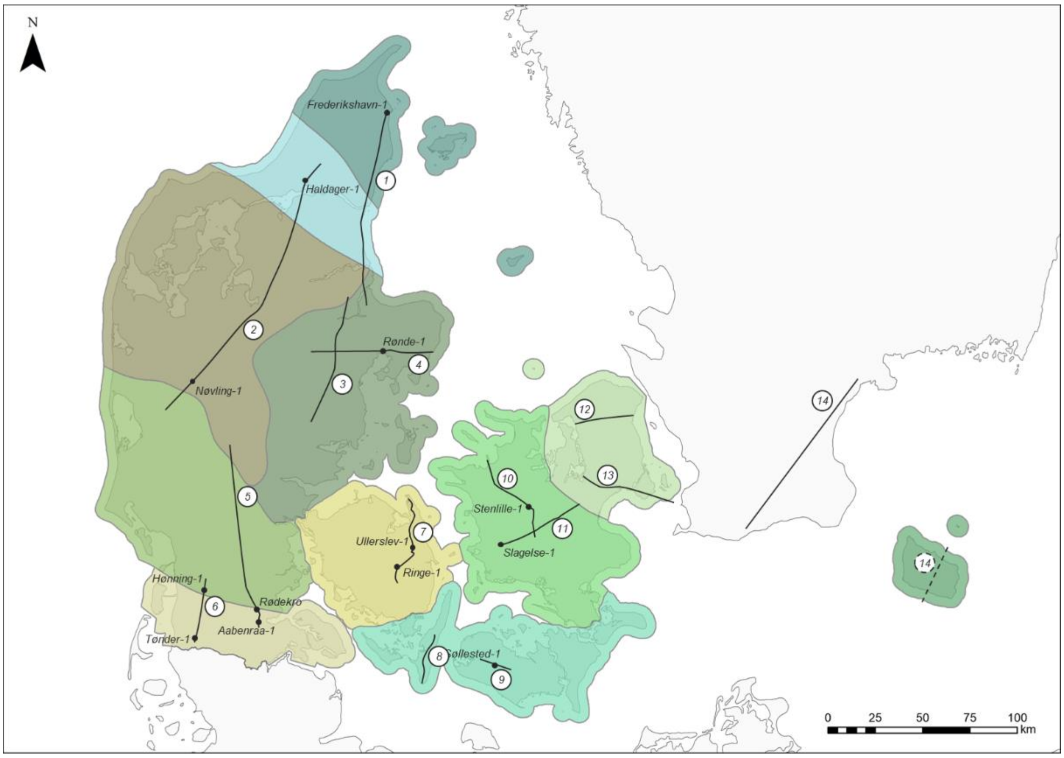


Figure 4.29. *Map showing the defined geological areas and the location of the cross-sections no's 1 to 14. Section no. 14 is from southern Sweden and represents an analogy to the geological setting on the island of Bornholm (stippled line 14).*

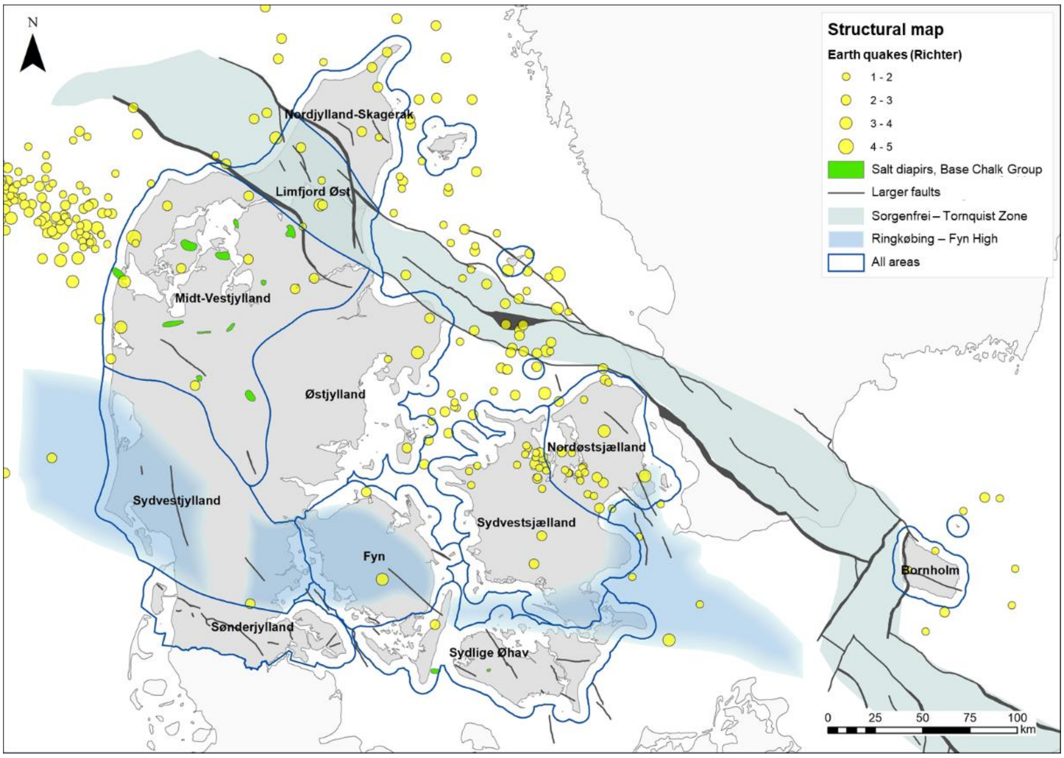


Figure 4.30. *Map showing the major structural elements at base of the Chalk Group, the epicenters of registered earthquakes and outlines of the defined geological areas. The estimated location of earthquake epicenters has an inherited uncertainty of 20 to 30 kilometers cf. Chapter 2, Report no. 7).*

Nordjylland area

The Nordjylland area is situated on the Kattegat-Skagerrak Platform (Figure 4.30). It is characterized by the presence of a relatively thick Cenozoic succession comprising predominantly Quaternary sediments. The succession reaches thicknesses of 350 meters in the northernmost part of the area (Figure 4.9). The 40–500 meters depth interval comprises carbonates from the Chalk Group. The base of the Chalk Group occurs at a maximum depth of around 700 meters. The Chalk Group thins towards the north where it pinches out due to uplift and erosion (Figure 4.10).

The Lower Cretaceous succession occurs in the 400 to 500 meters depth interval in two narrow belts formed due to tectonic compression and associated uplift in the northern part of the area (Figure 4.5). Several deep faults extending from the pre-Zechstein succession into the upper part of the Chalk Group occur in the area. The fault near the Frederikshavn-1 well extends to shallow depths and terminates in the Cenozoic succession (Figure 4.14). Several earthquakes have been registered in the area and the adjacent offshore areas.

Limfjord Øst area

The Limfjord Øst area is situated in the Sorgenfrei-Tornquist Zone (Figure 4.30) and is characterized by the presence of large faults related to the Sorgenfrei-Tornquist Zone. In large parts of the area the horizontal continuity of formations is limited due to off-sets along the fault planes. In most of the area carbonates from the Chalk Group constitute the depth interval from 500 meters to near surface and the Cenozoic succession thus varies in thickness from 0 to 100 meters (Figures 4.9, 4.10, 4.14 and 4.15). Lower Cretaceous claystone occurs in the interval from 500 meters to 1000 meters or more (Figure 4.4 and 4.10). Several earthquakes have been registered in the area and are possibly related to minor movements along the major faults identified from the seismic data.

Midt-Vestjylland area

The Midt-Vestjylland area is situated in the central part of the Danish Basin (Figure 4.30) where thick deposits of salt accumulated during the Zechstein time-period. The area is characterized by structural complexity with abundant faults and salt diapirs and rather discontinuous stratigraphic units displaying significant changes of thickness and depths over short distances (few kilometers) (Figures 4.14 and 4.15). Carbonates occur in the 400 to 500 meters depth interval in most of the area, and the carbonates continue downwards to depths exceeding 1000 meters. Characteristic for the area is the presence of a Cenozoic succession with a thickness of several hundred meters. In the southwestern most part of the area the thickness of the Cenozoic succession exceeds 600 meters and thus carbonate is absent both in the host rock interval and the overlying ECZ. Several earthquakes have been registered and they are possibly related to movements along faults that extend through the Cenozoic succession to near surface.

Østjylland area

The Østjylland area is situated in the Danish Basin south of the Sorgenfrei-Tornquist Zone (Figure 4.30). Carbonates from the Chalk Group crop out at surface locally in the eastern part of the area. The top of the Chalk Group occurs at increasing depths towards the southwest where it occurs at depths from 200 to 400 meters. Correspondingly the Cenozoic succession is thin to absent in the eastern parts of the area and reaches thicknesses of around 400 meters to the west where the top of the Chalk Group is at greatest depths (Figures 4.16

and 4.17). The carbonate thickness generally exceeds 1000 meters and is found in the depth interval from 400 to 500 meters. Several faults are identified in the area, some are associated with salt structures and others are related to the Sorgenfrei-Tornquist Zone. Most faults have only slight vertical off-set along the fault plane, and they terminate internally in the Chalk Group carbonates. However, some faults are observed to extend into the Cenozoic succession. A few earthquakes have been registered in the area.

Sydvestjylland area

The Sydvestjylland area is situated on the Ringkøbing-Fyn High (Figure 4.30). The area is characterized by a rather simple structural framework with horizontal bedding and horizontally continuous stratigraphic successions (Figure 4.18). The Cenozoic succession is rather thick especially to the west where it locally exceeds 600 meters in thickness. The top of the Chalk Group generally occurs at depths around 400 to 500 meters and the base of the Chalk Group is found at depths exceeding 800 meters. A few deep-seated faults are seen to extend into the Cenozoic succession. Only one earthquake has been registered in the area within the period of seismic monitoring.

Sønderjylland area

The Sønderjylland area is situated south of the Ringkøbing-Fyn High at the margin of the Northern German Basin (Figure 4.30). It is characterized by a Cenozoic section with a thickness exceeding 400 meters in most of the area (Figures 4.18 and 4.19). An east-west oriented salt ridge is present parallel to the Ringkøbing-Fyn High. Numerous deep faults extending into the Cenozoic succession occur in the area, related to remobilization of the Zechstein salt. Due to the presence of numerous faults and remobilized salt, the depth to top of various stratigraphic units changes significantly over short distances, thus resulting in limited horizontal continuity of the successions. In most of the area the interval from 400 to 500 meters comprises Cenozoic sediments and only in the easternmost part of the area is carbonate present in this interval.

Fyn area

The Fyn area is situated above the Ringkøbing-Fyn High (Figure 4.30) and is characterized by a relatively simple structural framework of the shallower successions (Figure 4.20). The top of the Chalk Group occurs at depths from 50 to 200 meters and the carbonate section continues to depths of 700 meters or more. The overlying Cenozoic succession is 50 to 200 meters thick with the greatest thicknesses to the south. The area is tectonically stable as it is situated above the quiescent Ringkøbing-Fyn High. The west-east trending structural high is bounded by a few major faults extending into the Cenozoic section. Few earthquakes are registered in the area.

Sydlige Øhav area

The Sydlige Øhav area is situated south of the Ringkøbing-Fyn High in the northern part of the North German Basin (Figure 4.30). The structural framework below the base of the Lower Cretaceous is complex and characterized by the presence of narrow east-west trending half-grabens filled by Jurassic sediments and bounded by deep-seated faults (Figures 4.21 and 4.22). Additional faults occur associated with remobilization of Zechstein salt. The top of the Chalk Group occurs at depths varying from ground level; as for example at the coastal cliffs of the island of Møn, to depths around 100 meters. The base of the Chalk Group occurs at depths of 400 to 600 meters in the central and southern parts of the area and generally the depth varies significantly over short distances. The depth interval 400 to 500 meters is thus composed variably of carbonates and / or Lower Cretaceous and Jurassic argillaceous sediments. The Lower Cretaceous succession is generally less than 50 meters thick, but the combined thickness of Lower Cretaceous and Jurassic successions locally reaches thicknesses of several hundred meters, however with significant variations over short distances (Figure 4.21). Most faults in the area terminate below or near the base of the Chalk Group whereas a few extend into the Cenozoic succession and possibly to near terrain surface. A few earthquakes have been registered in the area.

Sydvestsjælland area

The Sydvestsjælland area is situated in the eastern part of the Danish Basin (Figure 4.30). The top of the Chalk Group occurs at depths varying from surface level to 400 meters depth, with the greatest depths occurring in the northwestern part of the area. In the southern part of the area top Chalk generally occurs at depths varying from surface level to around 200 meters depth. The Chalk Group thickness increases from 700 meters in the southern part of the area to more than 1500 meters in the north. The thickness of the Cenozoic succession corresponds to the depth to the top of the Chalk Group and thus varies from 0 to 400 meters. Numerous faults occur in relation to remobilised salt (Figures 4.23 and 4.24). Most faults extend vertically to near base Chalk or slightly into the carbonate succession, but some faults are mapped to extend into the Cenozoic succession. Several earthquakes have been registered in the northern part of the area and are probably caused by minor movements along existing faults in the area.

Nordøstsjælland area

The Nordøstsjælland area is situated in the easternmost part of the Danish Basin and is bounded by the Sorgenfrei-Tornquist Zone to the east (Figure 4.30). The top of the Chalk Group occurs at depths from 50 to 150 meters and the Chalk Group thickness exceeds 1500 meters in most of the area. Several deep-seated fault systems with lateral displacement occur in the area. The faults are mapped to extend vertically to depths from around 100 to 50 meters below terrain. The mapped fault-termination at shallow depths suggests that fault movements may have occurred recently (Figures 4.25 and 4.26). Minor earthquakes are registered frequently in the area probably related to movement of faults within the adjacent Sorgenfrei-Tornquist Zone or other locally mapped.

Bornholm area

Bornholm is an island situated east of the Sorgenfrei-Tornquist Zone’s at the fault zone’s southeasternmost extension (Figure 4.30). Bornholm comprises two geologically different areas. In the northern and central parts, crystalline basement rock comprising Precambrian granite and gneiss occurs at shallow depths in a horst block bounded by major faults (Figure 4.31). The basement rocks are commonly covered by a thin succession of Quaternary sediments, and they crop out at numerous places in the area. The Bornholm area is not covered by seismic data and the geological model shown in Figure 4.27 is from southern Sweden where the structural setting can be regarded as an analogue to the geology of Bornholm. The model illustrates that in areas where the crystalline basement occurs at shallow depths it is expected to continue deep below the surface. The basement rocks will thus constitute both the potential host rock at 400 to 500 meters depth and overlying barriers in the ECZ. Within the basement area a few major faults have been mapped in addition to numerous factures visible at the surface. One earthquake has been registered on Bornholm in the observation period and a few are registered in the nearby offshore areas (Figure 4.30).

The southern part of Bornholm is characterized by the presence of numerous small, fault-bounded half grabens containing variable sedimentary deposits of different ages (Figures 4.28 and 4.31). Due to the very limited lateral extension of the sedimentary sections in each fault block this area is not considered as relevant for detailed site investigations of a potential host rock.

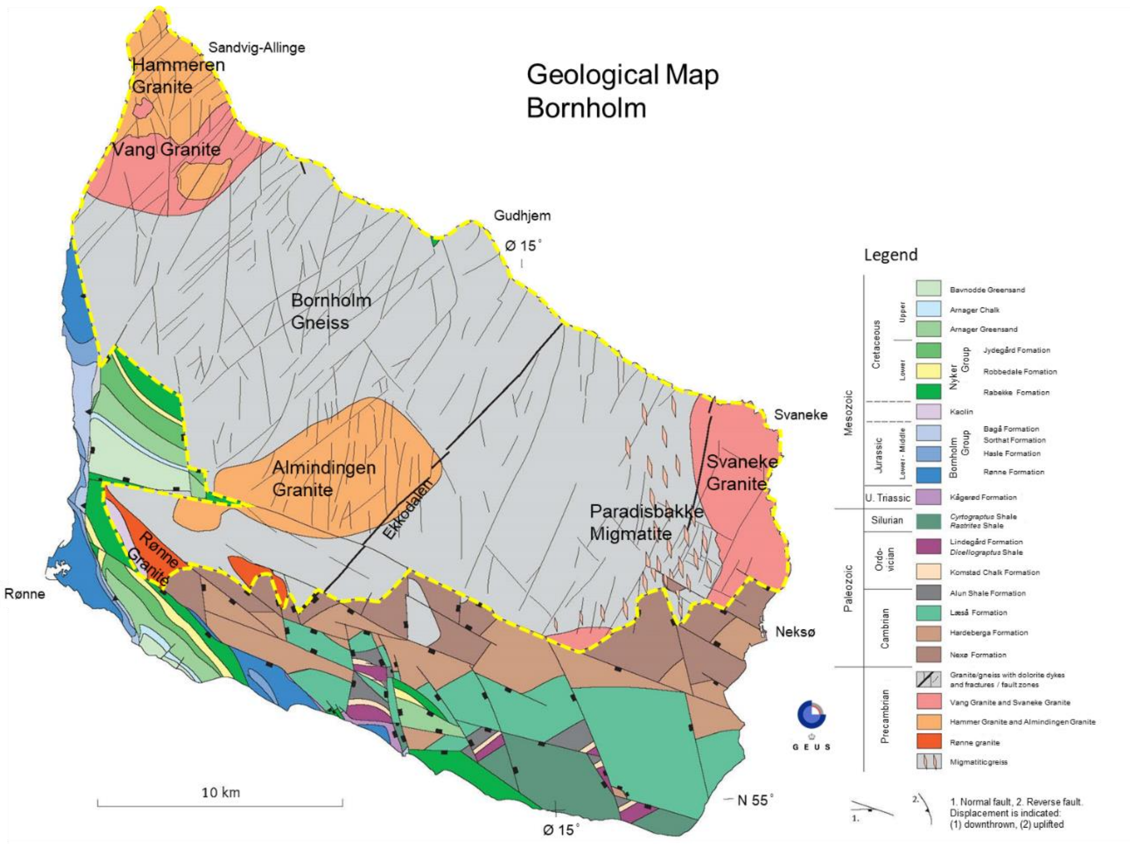


Figure 4.31. *Simplified geological map of Bornholm at the base of the Quaternary (modified from Varv, 1977). The yellow polygon outlines the area where crystalline basement rocks of granite and gneiss occur at or near surface.*

5. Application of criteria in area evaluation

For each criterion, geological properties or conditions that are regarded as being favourable have been defined. The presence of favourable properties is evaluated and scored, and subsequently the property scoring is used as the basis for the overall criteria evaluation. In the following section is a description of how the properties are evaluated and how they are used for a qualitative evaluation of the criteria. The criteria evaluation is presented by a colour score with three levels. As the amount of detailed data from depths around 500 meters in the Danish subsurface is limited, the evaluation of how geological properties and conditions fulfill the criteria is qualitative at this stage of the siting project.

Figure 5.1 shows a conceptual geological situation with the top of a host rock interval for disposal occurring in the 400–500 meters depth interval, and carbonates constituting the additional barrier in the overlying ECZ. The evaluation of whether criteria for the depths and thicknesses of potential host rocks and barriers in the ECZ are favourable is made with reference to the terminology shown (Figure 5.1). In areas where crystalline basement rocks occur at ground level the geological record is simple as these rocks constitute both the potential host rock and the barrier in the ECZ. Groundwater interests may exist in the uppermost part of the record in all areas. Groundwater interests occur extensively in fractured carbonates, in Cenozoic sand, and in fractured basement.

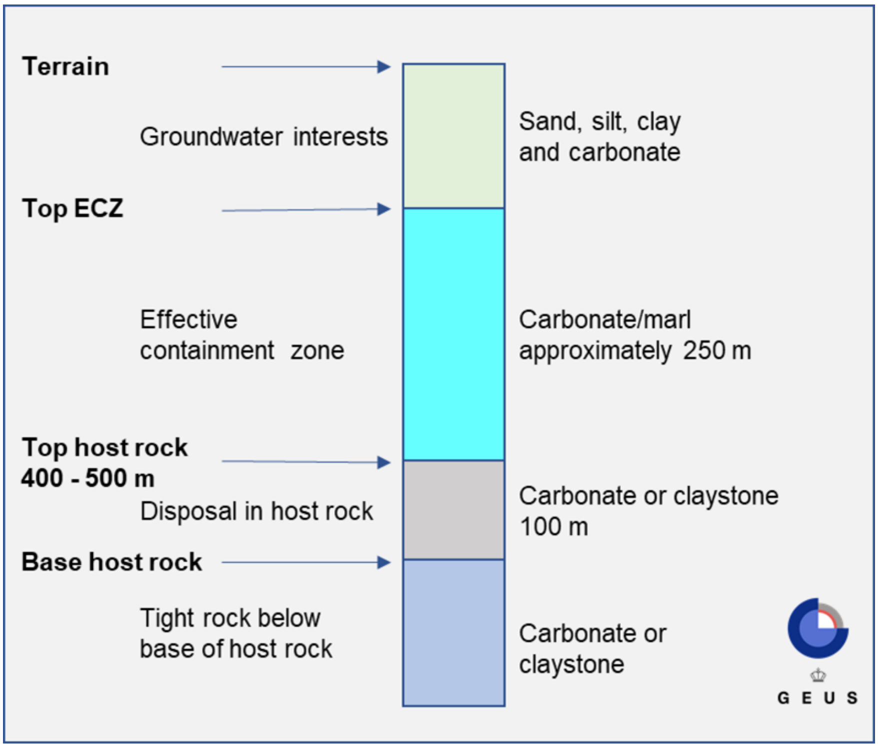


Figure 5.1. *The figure illustrates a conceptual sedimentary succession and the terminology applied for the criteria evaluation. The top of a host rock for deep geological disposal is located at a depth between 400 and 500 meters. Overlying is a 250 meters thick section of carbonates, which constitutes the barrier rock in the effective containment zone (ECZ).*

5.1 Properties of host rock and barriers in the ECZ

The geological requirements for a host rock as given in B90 (Danish Parliament, 2018) are a geologically homogeneous and low permeability formation with a thickness of at least 100 meters, which is laterally extensive without significant discontinuities. These requirements on the spatial extent are made to ensure that the geological properties and conditions can provide effective barriers in the subsurface, and that the geotechnical properties are suitable for the establishment of a repository. A homogeneous host rock with low permeability will promote a diffusion dominated transport of nuclide transport which occurs at extremely low rates. The host rock formation must be laterally continuous without major faults or other discontinuities to avoid nuclide transport by advective flow in fractures and high permeable zones that might constitute release pathways in the rocks.

The presence of low permeability sections overlying the host rock will provide additional barriers and the interval is referred to as the effective containment zone (ECZ, Figure 5.1). Formations in the ECZ must also be lithologically homogeneous and laterally continuous without major discontinuities in order to provide an efficient barrier to flow. The combined barrier effectiveness of the host rock and the ECZ must ensure the retardation of radioactive nuclides in the deep subsurface both in the short and long term.

Due to the scarcity of data from 500 meters depth in the Danish subsurface, the evaluation of permeability is at this stage largely inferred, based on the presence of clay in the sediments and the clay mineralogy. A high content of clay-sized particles and clay minerals will promote a low permeability of the rock and is therefore regarded as a favourable property. Additionally, the presence of the clay mineral smectite may retard nuclides by sorption and may thus promote geochemical retardation or retention of nuclide transport.

Specific geological properties that promote effective barriers in the host rock and the ECZ are listed in Table 5.1 (Criteria 1.1–1.4). In Report no. 1 (cf. References in Chapter 8.1) a detailed presentation of all criteria in this group and their relevance for safety in the short- and long-term is given.

Table 5.1. *A list of criteria and associated favourable properties and conditions for host and barrier rocks (criteria group 1)****.***

Criteria	Favourable properties
1.1 Spatial extent	• Host rock thickness is 100 m or more • Host rock occurs at around 500 m depth • Host rock has a lateral extent of 5x5 km or more • Host rock is lithologically homogenous (vertically and laterally) • Barrier rock is 250 m thick • Barrier rock has a lateral extent of 5x5 km or more • Barrier rock is lithologically homogenous (vertically and laterally)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport) • Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals • Host rock contains smectite • Barrier rock matrix has a high content of clay minerals • Barrier rock contains smectite
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock • Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth) • Laterally widespread, high-permeable layers are absent in barrier rock • Large open fractures, extending from host rock to the top of the barrier rock, are absent

5.2 Natural stability

A summary of properties and conditions related to natural stability is presented in Table 5.2. Reliable prediction of natural stability in the area is important to minimize the risk of the geological barriers being compromised by the formation of release pathways. Release pathways may be generated along fault planes of reactivated faults, from deep erosion into formations in the ECZ or from microfractures generated in the host rock or ECZ after closure of the repository.

The natural stability of the geological barriers in the area (criterion 2.1, Table 5.2) is evaluated based on the registered seismic activity and whether deep seated faults with fault-planes extending to near-surface are present. Potential reactivation of faults may result in the formation of microfractures along the fault planes which may constitute temporary flow fairways. Major faults can be identified and mapped in detail from closely spaced seismic data and areas and sites with major faults extending to near-surface positions can be avoided.

Another process that may compromise the geological barriers in the long term is glacio-tectonic deformation. Glaciotectonic deformation of sedimentary successions as thick as 300 meters is observed in costal cliffs and from seismic data. The deformation occurred due to the progression of thick ice-sheets formed during periods of glaciations (Reports no. 2 and no. 7, cf. references in Chapter 8.1). It is therefore assumed that deformation during future glaciations may reach as deep as 300 meters below ground level. However, it is predicted that the next glaciation will most likely occur at the time when a significant amount of the radioactive material has decayed. With the present CO_2 levels, the next glaciation has been modeled to take place in 100,000 to more than 800,000 years from now (Report no. 7, jf. references in Chapter 8.1).

The possibility that earthquakes will occur in the very near future exists mainly in areas where faults extending to surface or near-surface positions occur and where seismic activity has been registered. Thus, when evaluating and scoring the natural stability of an area (criterion 2.1) most emphasis is put on the risk of earthquakes as they may occur during the entire time period from today and until the radioactive material in the repository has decayed, thousands of years from now. Fault reactivation may cause temporary flow paths to be generated along fault planes and may occur at any time, thus the risk of fault movements has more impact on natural stability than the risk of deep glacial deformation which is unlikely to take place in the near future.

The risk that deep erosion may compromise the geological barriers is also evaluated. The Danish terrain is of low relief with altitudes varying from 0 to less than 200 meters above mean sea level. The low relief and the low tectonic activity in the Danish area means that the rate of surface erosion is small compared to areas with high gradients and high rates of tectonic uplift.

One process that may cause erosion to depths of several hundred of meters is glacial incision. The presence of glacial valleys in the Danish subsurface indicates that glacial incision occurred extensively to depths varying from a few tens of meters to several hundred meters locally. These valleys, referred to as buried valleys, are filled with sand and mudstone which often represent multi-layered deposits from several episodes of glacial erosion and subsequent deposition of sediments. The valleys have been reactivated several times showing that glacial erosion occurred predominantly in areas with pre-existing low relief and/or easily erodible unconsolidated sediments. It is therefore assumed that erosion during future glaciations will take place predominantly in areas with buried valleys and/or areas with relatively high surface relief such as rivers and fiords. TEM data has been used for the mapping of numerous buried valleys (Fig. 4.8) and areas where no valleys have been identified from the TEM data are assumed to be less exposed to future deep glacial erosion.

In case the repository compacts over time or gas pressure builds up, micro fractures may generate in the host rock and eventually propagate to the overlying barriers in the ECZ. If calcite or swelling clay such as smectite is present in the rocks, microfractures may self-heal and the effectiveness of the barriers will not be compromised.

Table 5.2. *List of criteria related to natural stability (criteria group 2) and the associated favourable properties and conditions.*

Criteria	Favourable Properties
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock

5.3 Geotechnical feasibility

In this initial phase of the geological siting project, the geotechnical properties of the subsurface are assessed only in general terms, based on the rock types and the tectonic setting of the areas, due to the absence of requirements related to a specific repository design concept and lack of data.

In the next project phase with detail geological investigations, emphasis will be put on the acquisition of geotechnical data for the investigation and characterization of the properties of each site. Geological properties and conditions that may have an impact on the geotechnical feasibility for construction of a deep repository and for the barrier effectiveness are listed in Table 5.3. Experience from constructions in the Danish subsurface exist mainly from depths less than 50 meters below surface and are related to quarrying and the construction of bridges, tunnels, and metro lines. One deeper construction in the Danish subsurface is the gas storage facility at Stenlille, where a cavern has been established in a high-permeablity sandstone at depths of around 1500 meters and in Lille Thorup where a cavern for gas storage was constructed in a thick formation of rock salt at 2–2.5 kilometers depth. This deep construction work was carried out using bore holes.

Geological conditions that may impact the subsurface geotechnical feasibility have been assessed preliminarily based on general knowledge. Isotropic tectonic stress is regarded as a favourable condition which is expected to exist in areas with horizontal layering and very low-angle dipping layers in the subsurface formations. In contrast, steeply dipping beds associated with major faults and/or salt structures are assumed to be associated with anisotropic stress conditions which is less favourable.

Laterally extensive layers or zones of high permeability rocks such as sand or fractured carbonate or granite may focus flow of ground water. The presence of high permeability zones is unfavourable due to the risk of discharge of large amounts of water into the construction site. Additionally, high permeability layers may have less strength, thus increasing the risk of instability which requires structural support of the construction.

Table 5.3. *List of criteria related to geotechnical feasibility (group 3) and the associated properties and conditions.*

Criteria	Favourable properties
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified • The host rock contains smectite or precipitated calcite in fractures • In the host rock, unconsolidated sand and fractures are absent • The barrier rock contains smectite or precipitated calcite in fractures • In the barrier rock, unconsolidated sand and fractures are absent • The barrier rock does not contain thick layers of plastic clay
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability • Large open fractures or faults extending from the surface to more than 500 m are absent

5.4 Reliability of new geological data

This group of criteria is relevant for the detailed geological site investigations. They are defined with the aim of evaluating whether proven and reliable data acquisition methods exist for generation of data for the characterization and evaluation of properties, if the surface terrain and geological conditions are suitable for the site investigations, and if data of high quality and low uncertainty can be provided (Table 5.4).

Characterization of rock properties from the site investigation requires detailed data on the lithological homogeneity/heterogeneity of the rocks, the mineralogical composition, variations in porosity and permeability and a geological setting where the rock properties can be expected to be highly representative within a distance of several kilometers from the borehole. A prerequisite for borehole data to be representative for a site is that the host rock and the ECZ formations are laterally homogeneous, occur at constant depth and that significant thickness changes do not occur over short distances.

The possibilities for detailed and precise mapping of formations in the subsurface depends on the thicknesses of individual lithological units and whether lithological contrasts at formation boundaries can be identified from seismic data (i.e. as a seismic reflector). A gentle surface topography and lithological homogeneity in the near-surface layers will have a significant impact on the possibilities for acquisition of high quality, high resolution geophysical data. A favourable situation is where surface layers are water saturated to shallow depths (near ground level) and without large morphological contrast such as locally occurring swamps, lakes, or dune fields.

The possibility for acquisition of data that can be used for evaluation and prediction of natural stability and potential future changes is also evaluated. Geological processes that are likely to influence the subsurface layers within the lifetime of a repository (thousands of years) can be identified and characterized based on knowledge about geological and tectonic development in the area and processes that have formed the landscape. By taking natural processes into account, the risk that the geological barriers of a repository will be compromised can be addressed and mitigated.

Table 5.4 *List of criteria related to reliability of new geological data (group 4) and the associated favourable properties and conditions.*

Criteria	Favourable properties
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data • Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped • Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data

5.5 Scoring of the geological properties

A qualitative evaluation of to what extent each criterion is fulfilled in each of the eleven areas is made based on existing data and knowledge. The evaluation is based on the predominating conditions in each area and does not include locally occurring variations, but local variations may be mentioned in the evaluation. When a criterion is scored as favourable in an area this means that reliable data show that most of the related properties fulfil the criteria in most of the area.

The criteria evaluation is carried out in two steps. The first step is an evaluation of whether favourable geological properties occur (Tables 5.1–5.4) and the result of this evaluation is presented as a sub-score with three levels (Figure 5.2). Based on all the sub-scores each criterion is subsequently scored qualitatively on a scale with three levels (Figure 5.3). The scores are defined as suitable, potentially suitable, and less suitable and the score is shown using green, yellow, and orange, respectively. The score represents an evaluation of both the geological properties and the level of confidence as determined by the amount and reliability (quality) of available data. This qualitative approach with a 3-level scale enables a relatively simple and transparent evaluation of to what extent the geological properties and conditions are suitable, or less suitable, based on the available data and knowledge.

Scoring of properties related to criteria:

- \- Data shows unfavourable properties related to criteria
- \+ Data shows partially favourable conditions, or data from analogues indicate favourable properties and conditions
- ++ Data from the area shows predominantly favourable conditions

Figure 5.2. *The evaluation of geological properties associated with each of the defined criteria (as listed in Tables 5.1–5.4), is presented with the assignment of a sub-score with three levels as shown in this figure. The sub-scores of properties related to each criterion provide the basis for the criteria evaluation where the evaluation is presented with a colour as illustrated in Figure 5.3. The sub-scores of properties and conditions for all areas is presented in detail in Enclosure A.*

Emphasis has been placed on ensuring a consistent and transparent criteria evaluation with regards to how the sub-scores are weighted and how many + and ++ result in a green or yellow score. All the sub-scores of properties and the scores of criteria together with relevant comments are presented in Enclosure A.

A green score for a criterion indicates that the related properties are predominantly suitable, and that the evaluation is based on representative and reliable (good quality) data. The green score also indicates that the risk of encountering data showing unfavourable conditions during the detailed site investigation is regarded as small. For criterion 1.1 on the spatial distribution of rocks, a favourable situation requires the presence of a 100 meters thick, horizontally extensive host rock at a depth around 500 meters **and** the presence of an overlying horizontally extensive barrier (in the ECZ), which in combination can provide the necessary geological barriers for deep disposal. For the evaluation of other criteria where properties are defined for both the host rock and the ECZ, the score for the host rock will be weighted highest as the presence of a host rock is a prerequisite for a deep geological repository. Furthermore, this is to honor that the geological requirements given in Danish Parliament's decision B90 (Danish Parliament, 2018) all relate to properties of the host rock.

A yellow score for a criterion indicates that some of the geological properties have been evaluated as favourable based on either limited data, data of questionable or fair quality and/or data from good representative analogues (same rock type and/or geological setting) presented in the literature. An example of data of fair quality could be a well log with low vertical resolution, or data from a borehole drilled to the stratigraphic interval of interest at a distance of tens of kilometers from the area. A yellow score thus indicates that favourable properties can be expected based on available data and analogues, however with some uncertainty associated with the evaluation. For properties with a yellow score, it is expected that the acquisition of new data will prove the presence of generally favourable properties, with only a minor risk that favourable properties and conditions will not be confirmed by the site investigations.

An orange score is given when reliable and good quality data indicates that the geological properties and conditions are generally less favourable, and do not fulfill the defined criterion. Specifically, for criterion 1.1 related to the spatial extension of rocks, a less favourable sub-score of a property related to the host rock will result in an orange score for the overall criterion. This is because a site can only be suitable for disposal at 500 meters depth if both a horizontally extensive host rock and a barrier in the ECZ are present. In areas where the horizontal continuity is less favourable due to the presence of numerous, closely spaced faults, comprehensive mapping is needed to identify areas with the required horizontal continuity to fulfill the criteria. In areas with closely spaced faults there is a risk that spatial extension cannot be confirmed by detailed site investigations. Additionally, if a high frequency of earthquakes is registered in areas where faults are mapped as extending to near surface, there is a significant risk of fault reactivation and associated occurrence of earthquakes. In these cases, detailed seismic mapping is highly important to avoid sites where long-term stability may be compromised by fault reactivation and associated formation of flow paths.

An orange score of one or several criteria in an area does not mean that potential sites for deep geological disposal cannot be identified in the area. Rather, an orange score indicates that less favourable properties must be mitigated by the presence of other favourable properties, or by the design of the facility and the engineered barriers. One example could be an area where the thickness requirements for barriers in the ECZ are not fulfilled, but the geochemical properties are very favourable and contribute significantly to the required retardation of nuclides. Another situation could be an area where a host rock with favourable properties exists only at depths below 500 meters, which is too deep to fulfill the criteria on spatial distribution. In this situation it might be considered whether disposal at a depth exceeding 500 meters could be a feasible option.

Score	Supporting data
Suitable	Reliable data shows predominantly favourable properties. Little uncertainty
Potentially suitable	Data and / or analogues indicate that favourable properties are expected to be present, however with some uncertainty
Less suitable	Reliable data shows that geological properties and conditions generally do not fulfil the defined criteria

Figure 5.3. *Overview of the colour scores that are applied in the criteria evaluation.*

6. Area characterization and evaluation

For each area, a qualitative evaluation is made on whether the geological properties and conditions related to each of the criteria are favourable. In areas where both carbonate and claystone occur at depths of around 500 meters, an evaluation has been made for each type of potential host rock. The evaluations are based on the knowledge about the properties of carbonate, claystone and basement as summarized in Chapter 3. Data regarding local geological properties and conditions are presented as figures and maps for each area.

The results of the criteria evaluation are presented with a short description of favourable properties and conditions for each area. Criteria evaluated as being less favourable are briefly explained with regards to the selection of a site for detailed geological investigations in the project’s next phase. In some cases, the potential implications for a deep disposal concept in the area is discussed briefly with comments regarding identified potentially mitigating actions.

Each section (sections 6.1–6.11) includes a map of the area's geographical extent and the location of municipal boundaries, refences to geological cross-sections that illustrate the typical stratigraphy and structural geological framework of the area, and a map presenting the seismic database and deep wells. Lithological interpretations of representative borehole logs of the 0 to 800 meters depth interval, and descriptions of drill cores, where available, from the potential host rock interval are presented subsequently. These figures illustrate the lithology and homogeneity (or inhomogeneity) of the potential host rock, and the barriers in the overlying ECZ. The barrier rock is carbonate in all areas except for Bornholm where basement provides both the potential host rock and the barrier in the ECZ (as illustrated in Figures 2.3 and 5.1). Petrophysical log interpretations from boreholes have been used to evaluate criteria 1.1, 1.2, 1.3, 1.4, 2.3, 3.1, 3.2 and 4.2.

Detailed depth and thickness maps are shown for all the mapped intervals in all areas for the sake of completeness, even though some intervals occur at depths exceeding the 500 meters depth of interest. Detailed depth and thickness maps are presented for the same stratigraphic intervals as presented in the regional maps in Chapter 4 (Figures 4.4–4.12). The geological maps and cross-sections are used for the evaluation of geological properties and conditions related to criteria 1.1, 2.1, 2.2, 3.1, 3.2, 4.1 and 4.3.

The evaluation of natural stability is based on recorded earthquakes, the presence of major faults, and buried valleys. A map of land use is included since the presence of large areas occupied by lakes and inlets, and areas with highly varying geomorphology and associated different types of terrain, may influence the potential for acquisition of reliable and high-quality data.

A detailed evaluation of each area is presented in Appendix A. Here, the sub-scores of the geological properties which provide the basis for the geological evaluation of each criterion are presented. Local variations of properties within the individual areas are generally not considered in the scoring, however, comments on variations or special conditions are included where relevant.

Emphasis has been placed on making a consistent criteria evaluation by ensuring that the type and amount of knowledge and data, together with specific local properties and conditions are weighted and scored equally for each area.

6.1 Nordjylland

In most of the area, carbonates occur in the depth range from 400 to 500 meters, whereas Lower Cretaceous claystone is present locally at this depth (Figures 4.14 and 6.6). Thus, both carbonate and claystone are considered as potential host rocks in the Nordjylland area, and an evaluation of both rock types has been carried out. The presence of several faults, including transverse faults with horizontal displacement and normal faults with vertical displacement, may limit the horizontal continuity of the geological formations (Figure 4.14).

Claystone host rock (Lower Cretaceous and Jurassic)
Claystone occurs in the Lower Cretaceous and Jurassic sections. The combined thickness is more than 500 meters (Figure 6.12) and in the northernmost part of the area, claystone is locally present in the 400–500 meters depth interval (Figures 6.6 and 6.7).

The claystone section is inhomogeneous as it consists of alternating layers of clay, silt, and fine sand as seen in the Frederikshavn-1 well (Figures 6.3 and 6.4) and the Haldager-1 well (Figure 6.19). Criterion 1.1 has therefore been given an orange score (Table 6.1) since a 100 meters thick section of homogeneous clay has not been identified in the area. Additionally, the carbonate barrier rock in the ECZ is 0–200 meters thick, i.e., less than the required thickness of 250 meters (criterion 1.1), and it wedges out towards the north (Figures 4.14 and 6.10). Quaternary deposits reach thicknesses of up to 350 meters in the Cenozoic section in the northern part of the area (Figure 6.9).

Jurassic sediments occurring at depths of around 500 meters immediately below the potential clay host rock contain sand layers that can act as flow paths (Figure 6.3). Therefore, criterion 1.4 is scored as less suitable (orange).

Due to the structural complexity the potential for reliable rock characterization based on new data is scored as potentially favourable (yellow). It will be challenging and time consuming to identify sites where data from new boreholes drilled into the subsurface formations can be expected to be representative for the entire site, due to large variations in thicknesses and depths over short distances.

Table 6.1. *Evaluation of claystone host rock (Lower Cretaceous and Jurassic), Nordjylland.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

Carbonate host rock (Upper Cretaceous Chalk Group)

In most of the area the total thickness of the carbonate section is 0 to 200 meters, and it generally constitutes the depth interval 400 to 200 meters below terrain in most of the area. Towards the north the carbonate section pinches out due to erosion (Figure 6.10). Thus, the total thickness of the carbonate section does not fulfill criterion 1.1; 100 meters thickness of host rock and 250 meters of barrier, and therefore the spatial extent criterion 1.1 is scored as less suitable (orange). However, locally in the southernmost part of the area, carbonates are present with thicknesses of 100 meters at depths around 500 and 250 meters in the overlying ECZ meters. Thus, locally, sections of carbonate can form both a potential host rock and an overlying barrier. Sections of Quaternary deposits reach thicknesses of up to 350 meters in the northern part of the area (Figure 6.9) and are not regarded as a potential barrier.

When considering whether to establish a repository at depths greater than 500 meters, in order to fulfill the requirements on the spatial extent of host rock and barriers, the presence of unconsolidated sand in the thick Cenozoic succession of mainly glacial Quaternary sediments may compromise the geotechnical feasibility.

Due to the structural complexity and significant variations of depth to geological unit boundaries over short distances, the potential for reliable rock characterization based on new data is scored as potentially favourable (yellow). It will be challenging and time consuming to identify sites where data on rock properties from new boreholes drilled into the subsurface formations can be expected to be representative for the entire investigation site of minimum 5x5 kilometers.

Table 6.2. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Nordjylland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

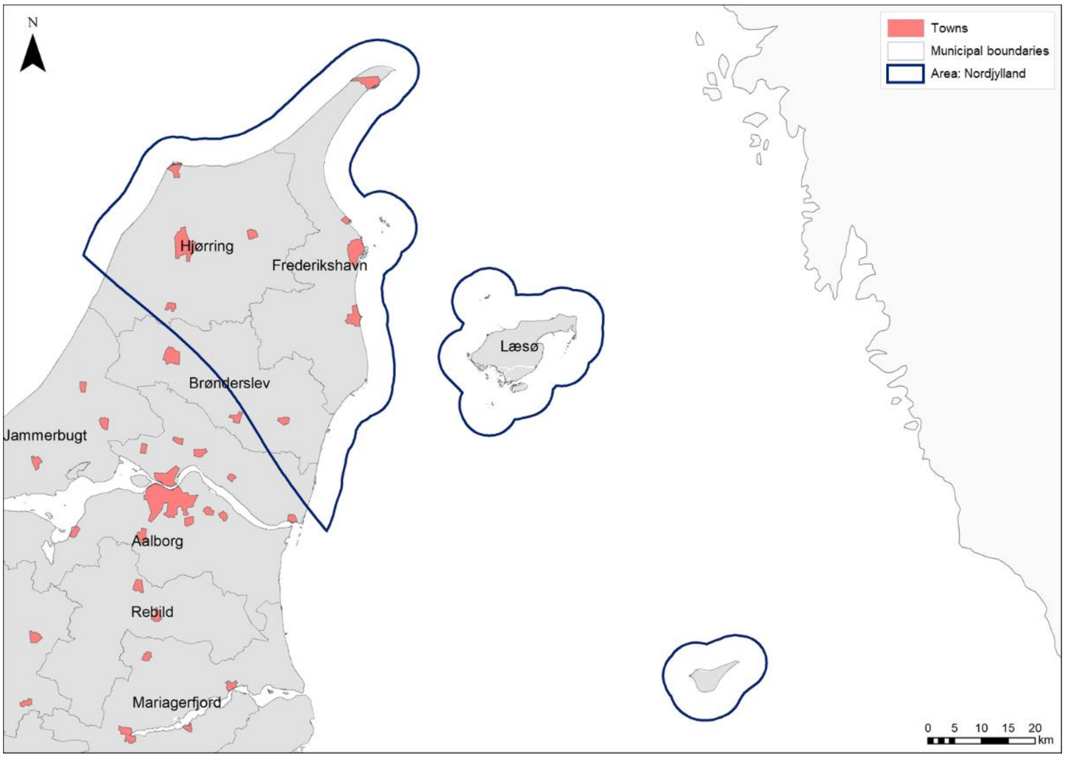


Figure 6.1. *Geographic outline of the Nordjylland area (including the islands of Læsø, and Anholt to the south) with municipal boundaries and towns indicated.*

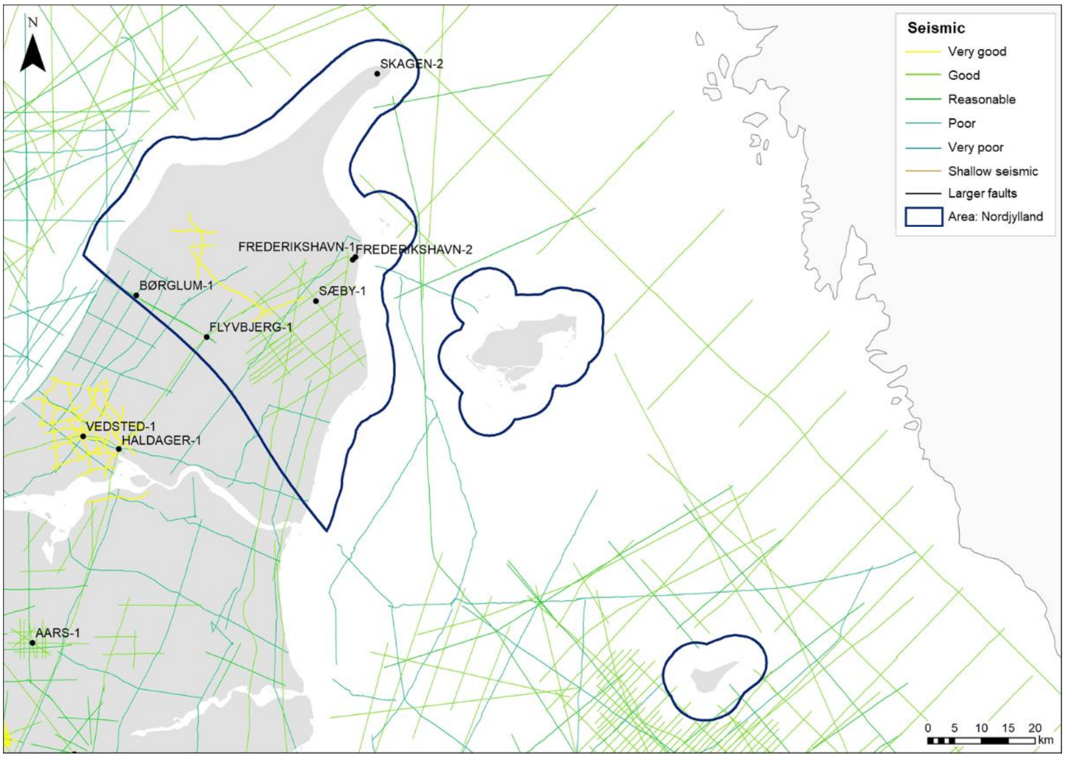


Figure 6.2. *Location map showing seismic lines and their quality, and deep boreholes in the Nordjylland area.*

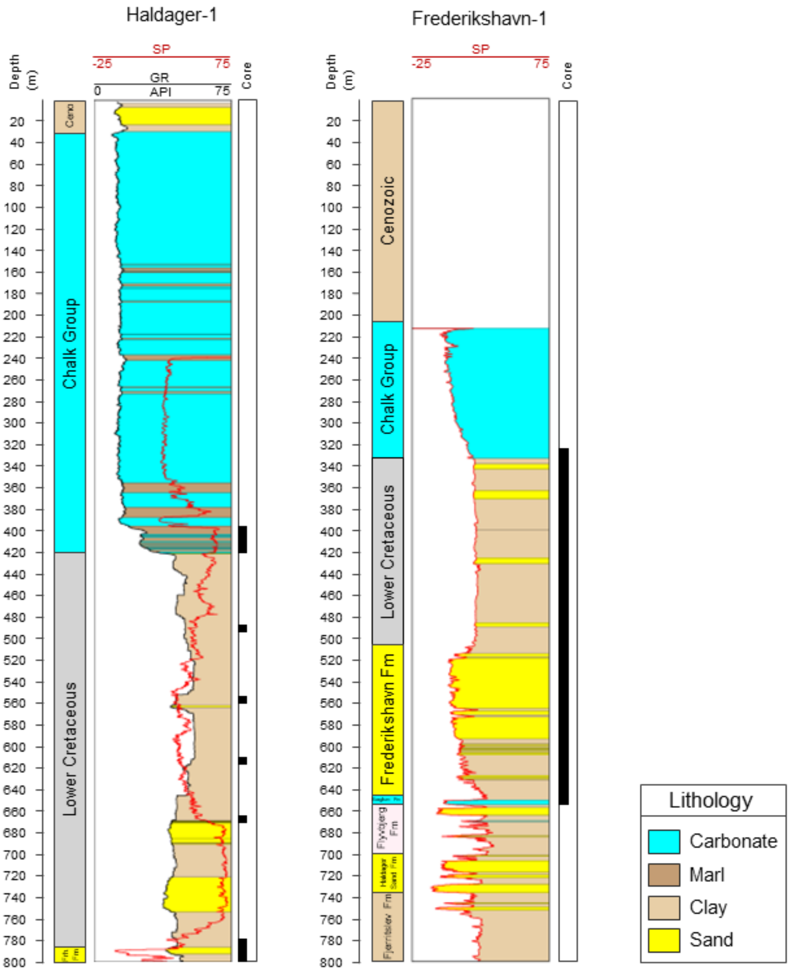


Figure 6.3. *Lithological logs based on petrophysical well log interpretations of the 0–800 meters depth interval in the Haldager-1 (Limfjord Øst area) and Frederikshavn-1 (Nordjylland area) boreholes. In the Haldager-1 log, carbonate constitutes the interval from approximately 40 meters to 400 meters, and below is an interval of Lower Cretaceous clay with interbedded sand layers. In the Frederikshavn-1 well log, the carbonate section in the barrier zone is 150 meters thick and is overlain by 200 meters of Cenozoic sediments (not logged). From the well log interpretation, the Lower Cretaceous interval in Frederikshavn-1 is shown to be dominated by clay, probably due to limited vertical resolution of the well logs, since numerous sand layers are recorded from the core description shown in Figure 6.4. Due to the lithological variations observed from cores of the clay-dominated sections, they are not regarded as being lithologically homogenous.*

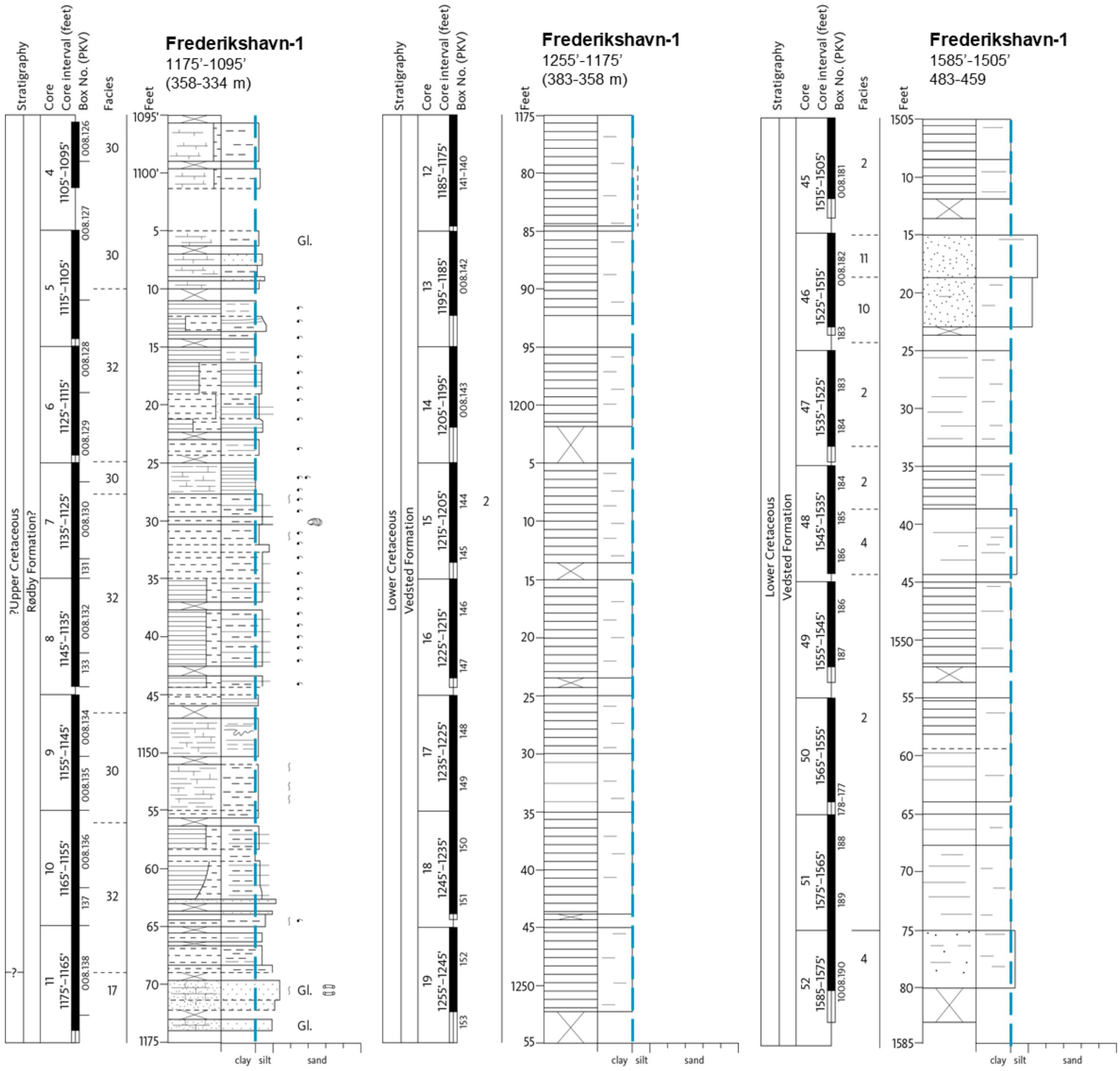


Figure 6.4. *Sedimentological logs of representative intervals from the Lower Cretaceous Rødby and Vedsted Formations in the Frederikshavn-1 well. The boundary between the clay and silt grain sizes is shown with the dotted blue line to highlight the vertical variations in grain size and the presence of sand layers. The log in the middle shows the presence of 80 feet (approximately 25 meters) of homogeneous clay, while the other two logs show sections that are lithologically less homogeneous.*

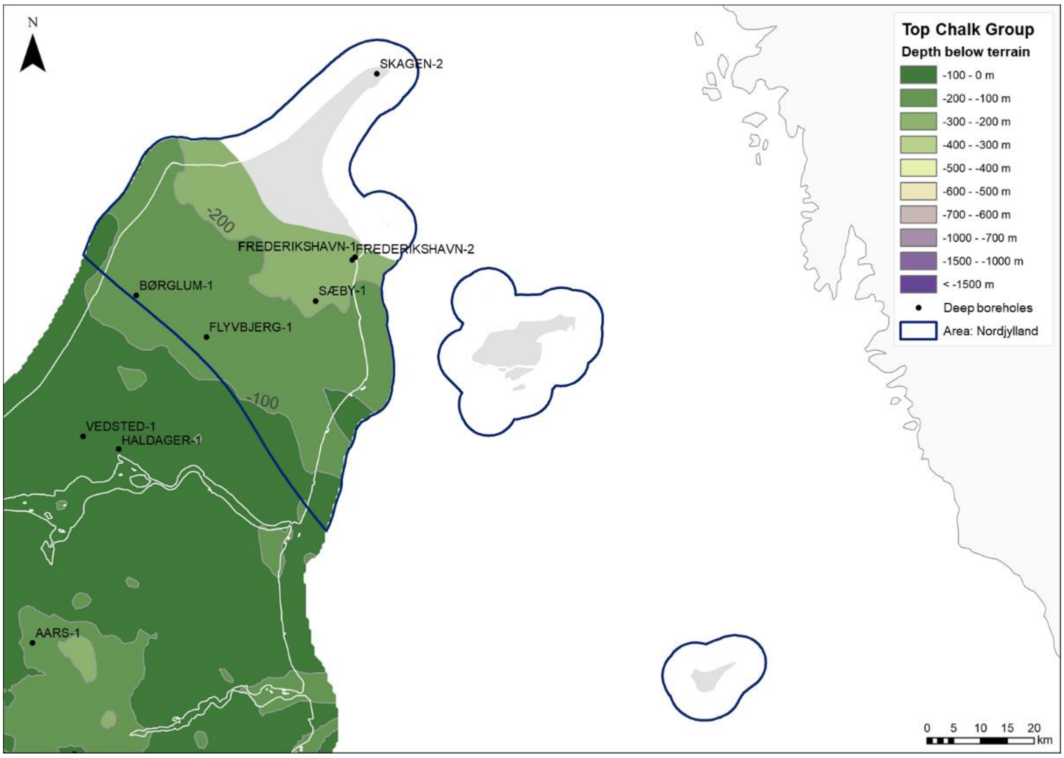


Figure 6.5. *Top Chalk Group depth map, Nordjylland area. The depth to top Chalk is generally between 100 and 200 meters. The Chalk Group is absent north of Frederikshavn.*

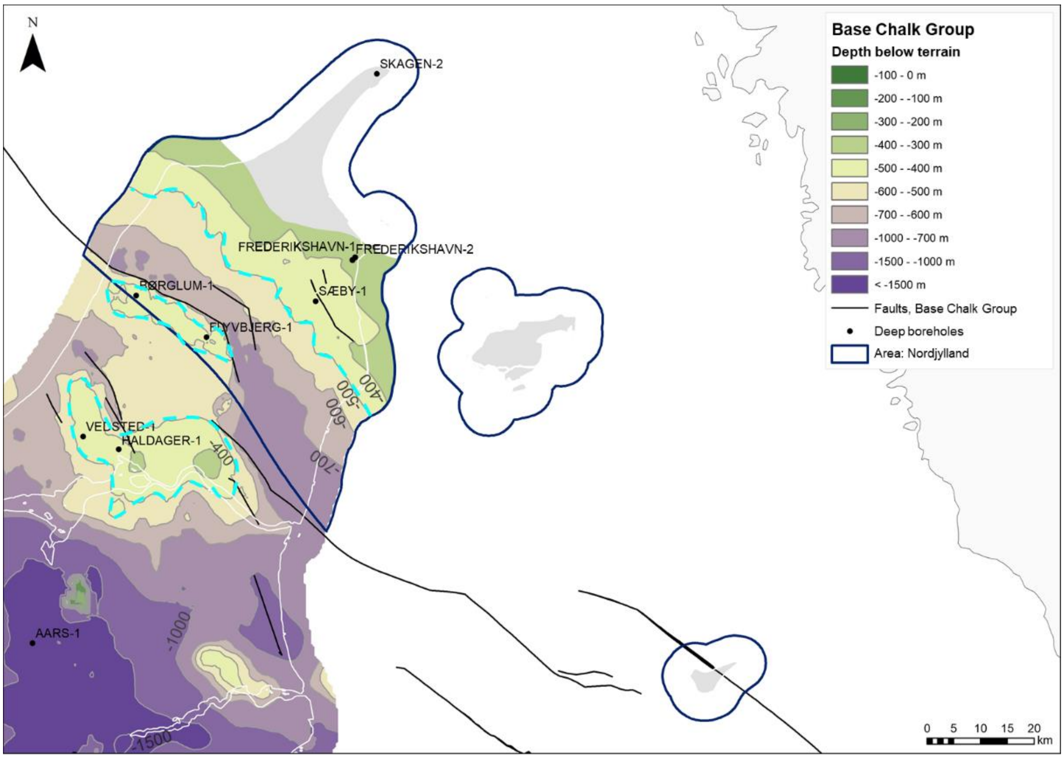


Figure 6.6. *Top Lower Cretaceous (base of the Chalk Group) depth map, Nordjylland area. Mapped faults intersecting the base of the Chalk Group are indicated. In the area north of the dotted line, as well as within the small polygon, top Lower Cretaceous occurs at depths of 300–500 meters, whereas it occurs at greater depths in the remaining part of the area.*

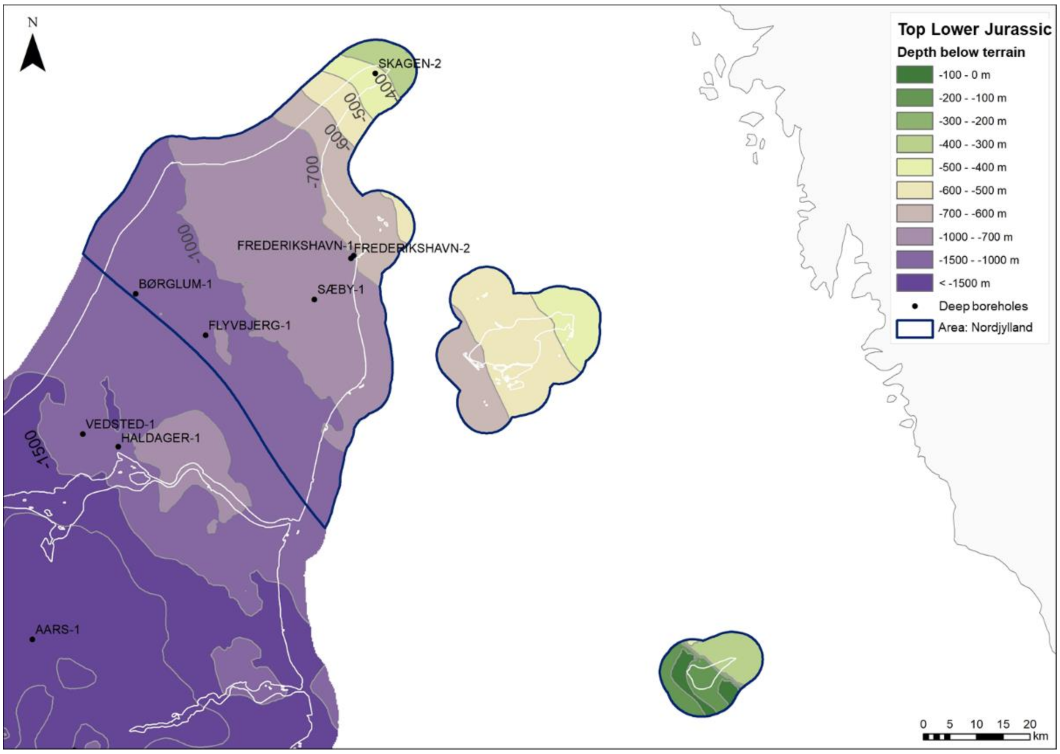


Figure 6.7. *Top Lower Jurassic depth map, Nordjylland area. Top Lower Jurassic occurs at depths around 700 meters in the north and increases to more than 1000 meters in the southern part of the area.*

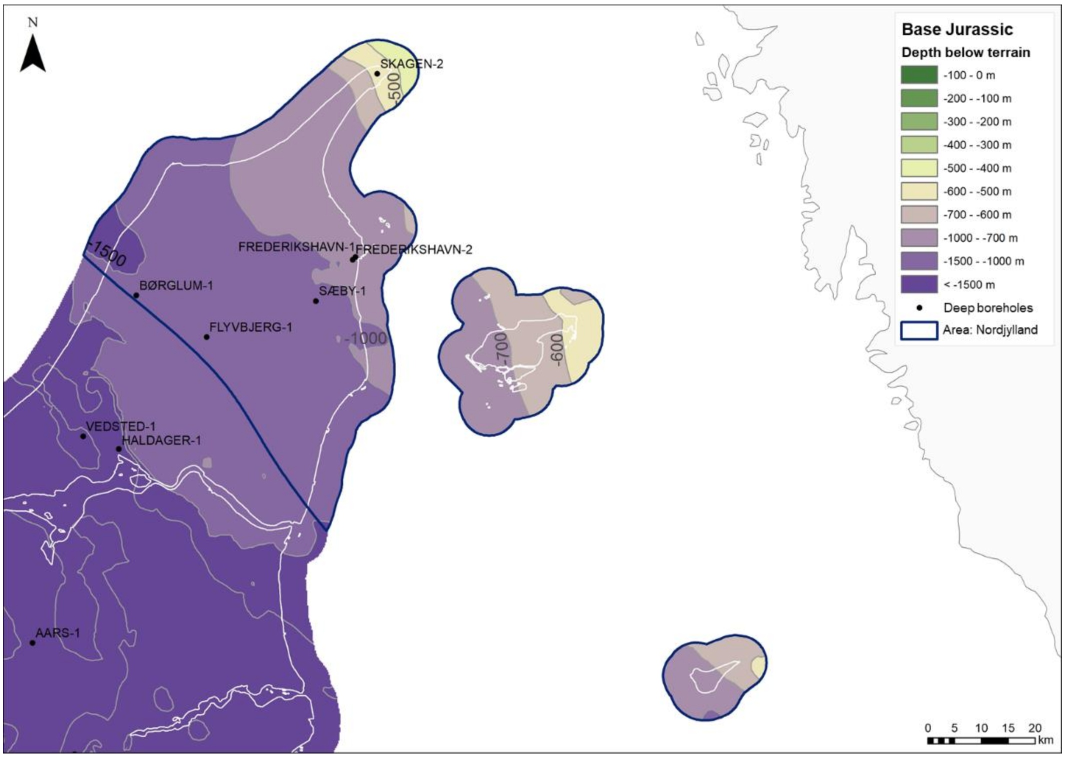


Figure 6.8. *Base Jurassic depth map, Nordjylland area. The base of the Jurassic is generally found at depths exceeding 700 meters.*

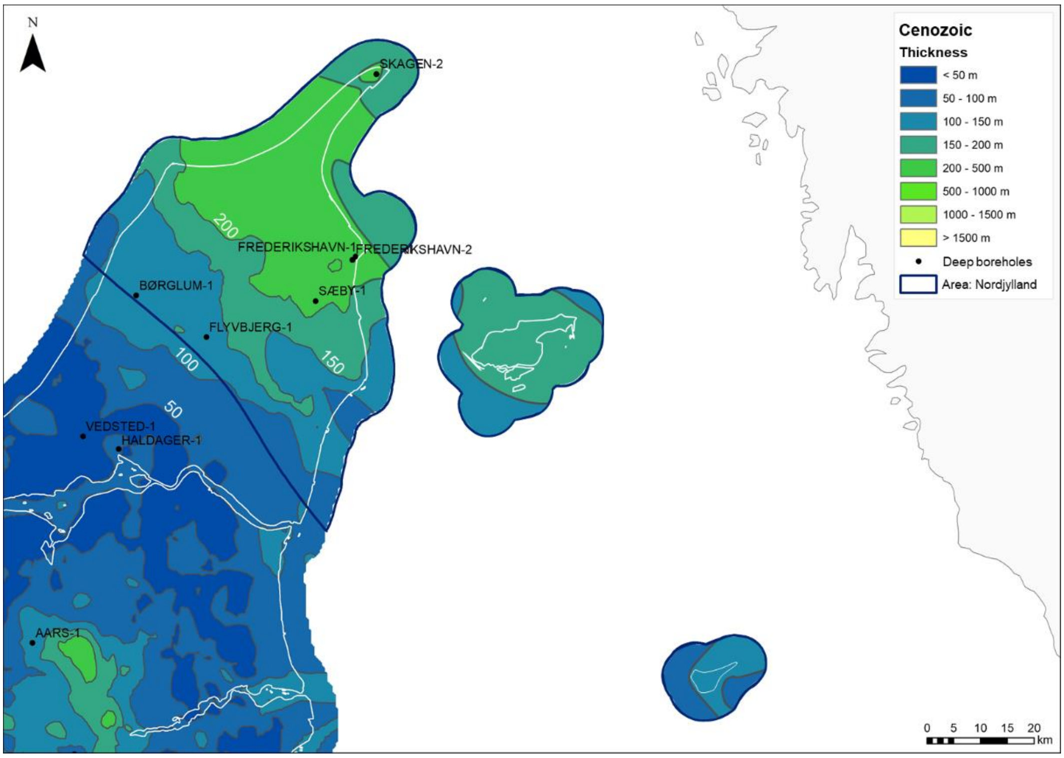


Figure 6.9. *Map showing the Cenozoic thickness in the Nordjylland area. The thickness varies from 100 meters in the south to 300 meters in the north (light green area) where it is composed of Quaternary sediments.*

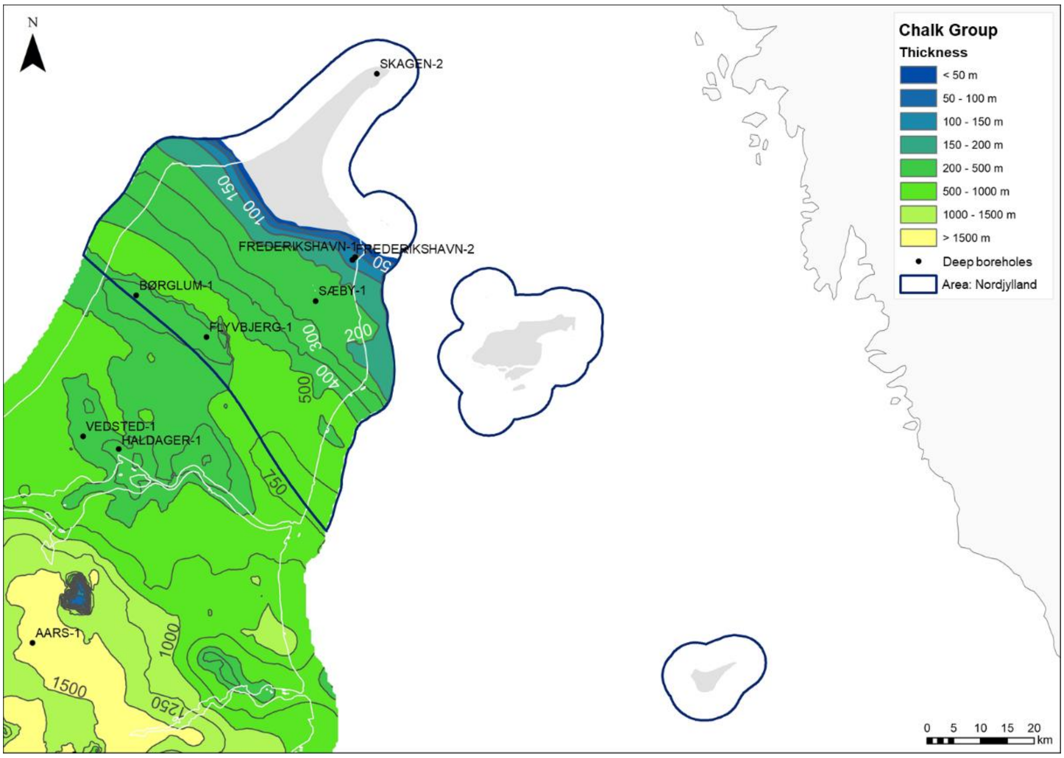


Figure 6.10. *Map showing Chalk Group thickness in the Nordjylland area. The thickness varies from more than 500 meters in the south (light green areas) to 150 meters close to the Frederikshavn-1 borehole and further north it pinches out.*

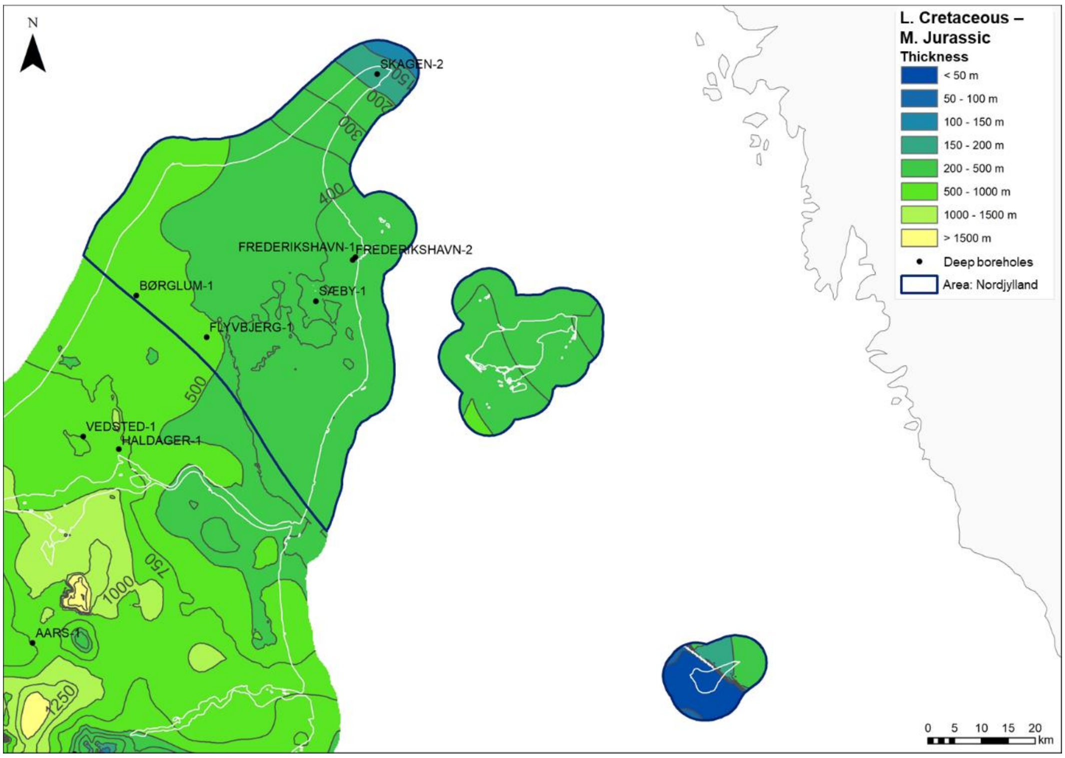


Figure 6.11. *Map showing the thickness of the Lower Cretaceous to Middle Jurassic section, Nordjylland area. The thickness is generally between 400 and 500 meters.*

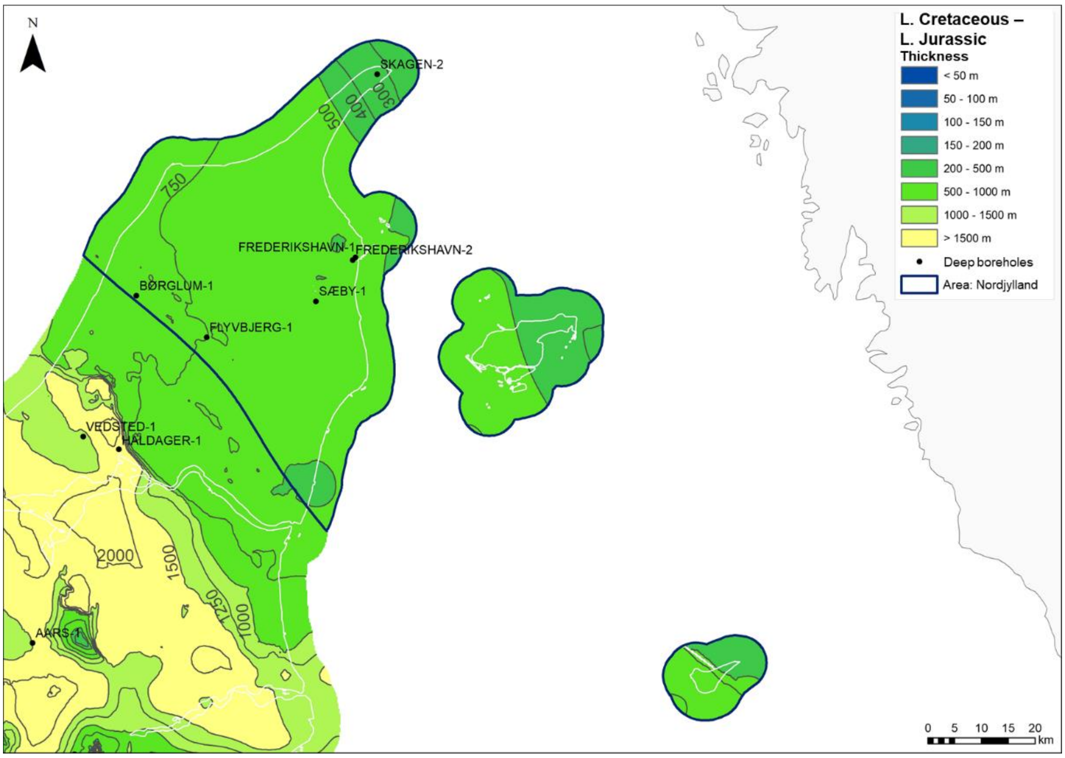


Figure 6.12. *Map showing the total thickness of the combined Lower Cretaceous and Jurassic sedimentary sections, Nordjylland area. The thickness is generally between 500 and 700 meters.*

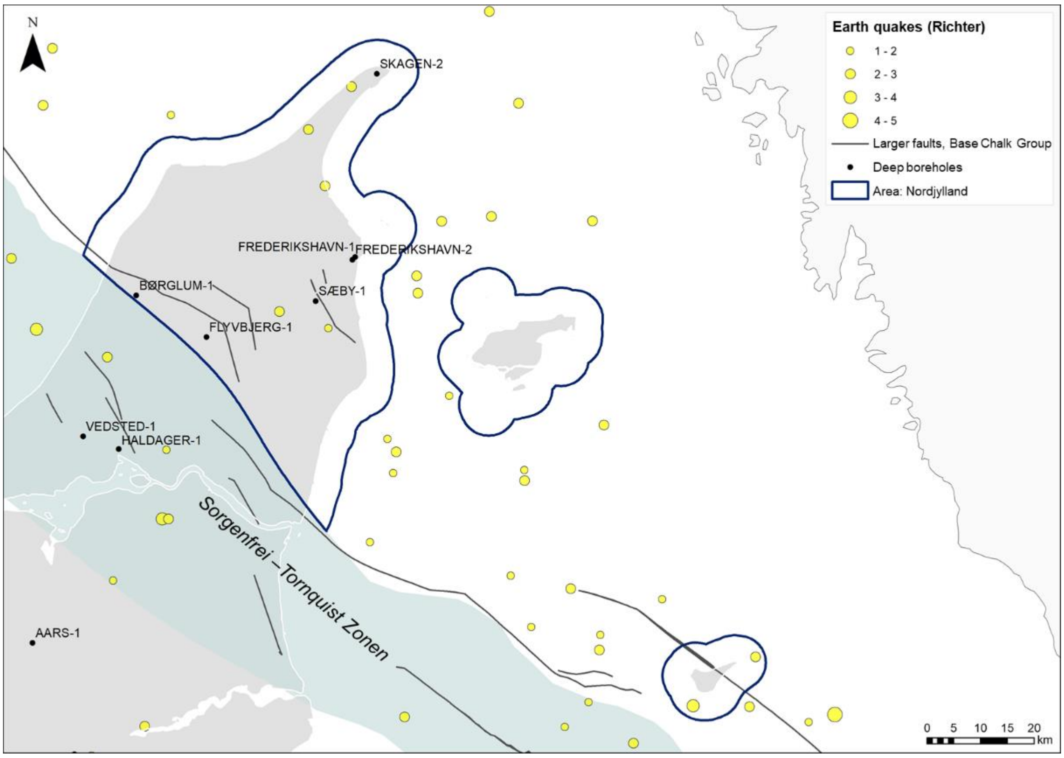


Figure 6.13. *Earthquakes registered during the past 50 years plotted on a structural map, Nordjylland area. The magnitude of the earthquakes is from 1 to 3 on the Richter Scale.*

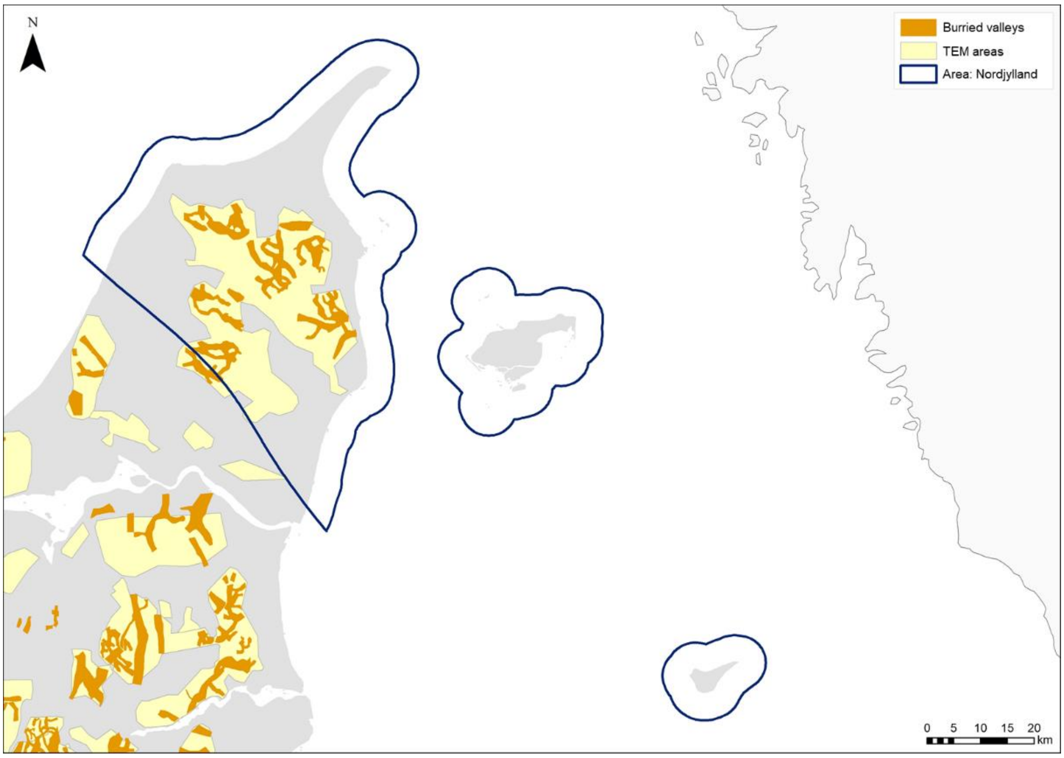


Figure 6.14. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Nordjylland area.*

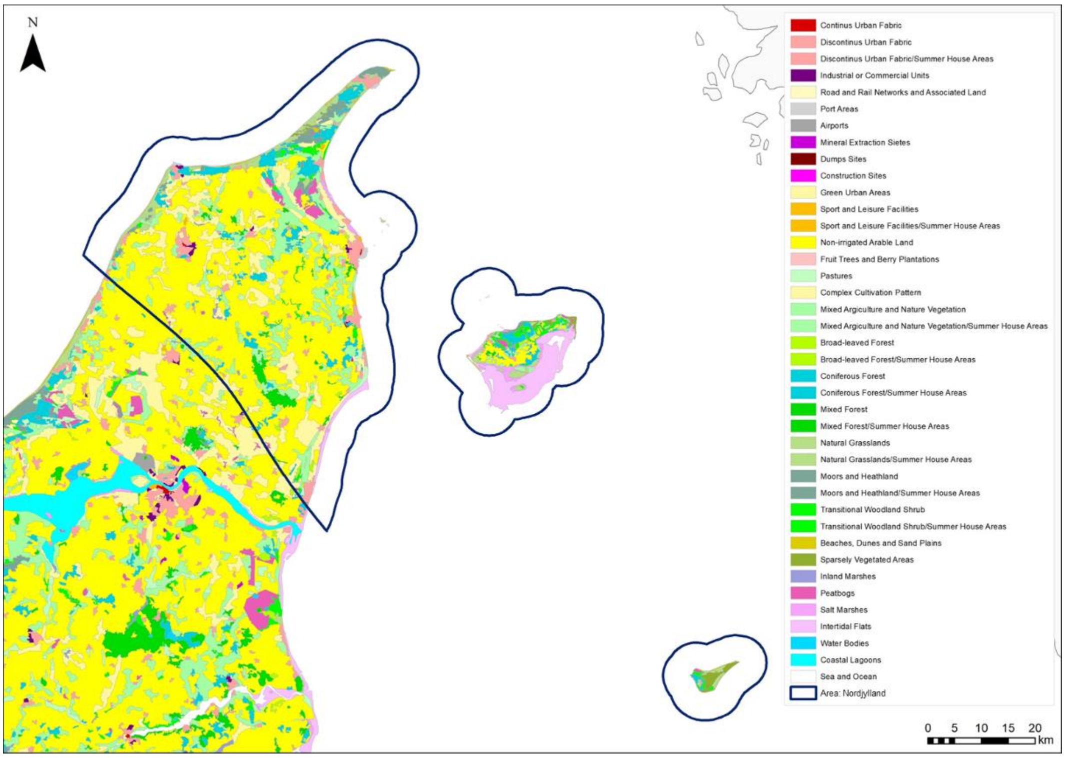


Figure 6.15. *Land use, Nordjylland area (MiljøGIS, 2021).*

6.2 Limfjord Øst

In most of the area, the 400–500 meters depth interval consists of carbonate. Claystone from Lower Cretaceous and Jurassic is generally present from 500 meters and deeper, although locally the top of the claystone section occurs at depths shallower than 500 meters (Figures 6.20 and 6.21). Therefore, since both carbonate and claystone are potential host rocks, an evaluation of each scenario has been made. The geological cross-sections (Figures 4.14 and 4.15), show the presence of numerous faults in the Limfjord Øst area which reflect its location in the Sorgenfrei-Tornquist fault zone. The presence of numerous faults may compromise the horizontal continuity of geological formations in the area.

Claystone host rock (Lower Cretaceous and Jurassic)
Homogeneous claystone sections with a thickness of 100 meters have not been identified at depths around 500 meters. The combined thickness of Lower Cretaceous and Jurassic sections varies from 700 to more than 1500 meters (Figure 6.27), but the available data shows the section is very heterogeneous. Lithological and sedimentological logs from the Haldager-1 and Frederikshavn-1 wells (Figures 6.18 and 6.19) show the presence of abundant sand and silt layers in the 340 to 800 meters depth interval, and criterion 1.1 on lithological homogeneity is not fulfilled and results in an orange score. Locally, in the central part of the area, the top of the Lower Cretaceous occurs at depths of around 500 meters but in most of the area it occurs at significantly greater depths (Figure 6.21).

The horizontal continuity of the host rock section is limited due to the presence of numerous, closely spaced faults (Figure 4.15, near the Haldager-1 well) and contributes to the less suitable scoring for criterion 1.1.

The numerous sand layers occurring in the claystone interval at 500 meters depth and deeper may act as release pathways where water flow can occur at the base of a deep repository. This is a less suitable situation for criterion 1.4 and gives an orange score.

Table 6.3. *Evaluation of claystone host rock (Lower Cretaceous and Jurassic), Limfjord Øst area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	(orange)
	1.2 Hydraulic barrier effectiveness	(yellow)
	1.3 Geochemical conditions for retardation	(yellow)
	1.4 Release pathways	(orange)
2. Long-term natural stability	2.1 Stability of the site and rock properties	(yellow)
	2.2 Erosion	(yellow)
	2.3 Repository induced influences	(green)
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	(yellow)
	3.2 Underground access and drainage	(yellow)
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	(green)
	4.2 Explorability of spatial conditions	(yellow)
	4.3 Predictability of long-term changes	(green)

Carbonate host rock (Upper Cretaceous Chalk Group)
In most of the area, carbonate comprises the interval from 400 to 500 meters and the carbonates continue upwards to depths of around 100 meters, and locally to ground level (Figures 4.14, 4.15 and 6.20). Carbonates therefore constitute both the host rock and the barrier rock in the ECZ. The base of the Chalk Group occurs at 500 meters or deeper and the carbonate thickness varies between 300 and 1000 meters (Figures 6.21 and 6.25).

Several deep faults extend to the base of the Chalk Group. Some of the faults continue into the Chalk Group and may limit the horizontal continuity of carbonate host rock in the area. However, large parts of the area appear to be relatively undisturbed without major displacements along the identified faults.

The Lower Cretaceous section occurring immediately below the Chalk Group contains high porosity sand layers in the Haldager-1 and Frederikshavn-1 wells (Figures 6.4, 6.18 and 6.19), which may act as flow paths. If an investigation site is selected where the base of the Chalk Group occurs near 500 meters depth, the potential presence of sand layers immediately below the base of the Chalk Group should be investigated to ensure that potential flow paths are absent.

Table 6.4. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Limfjord Øst area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

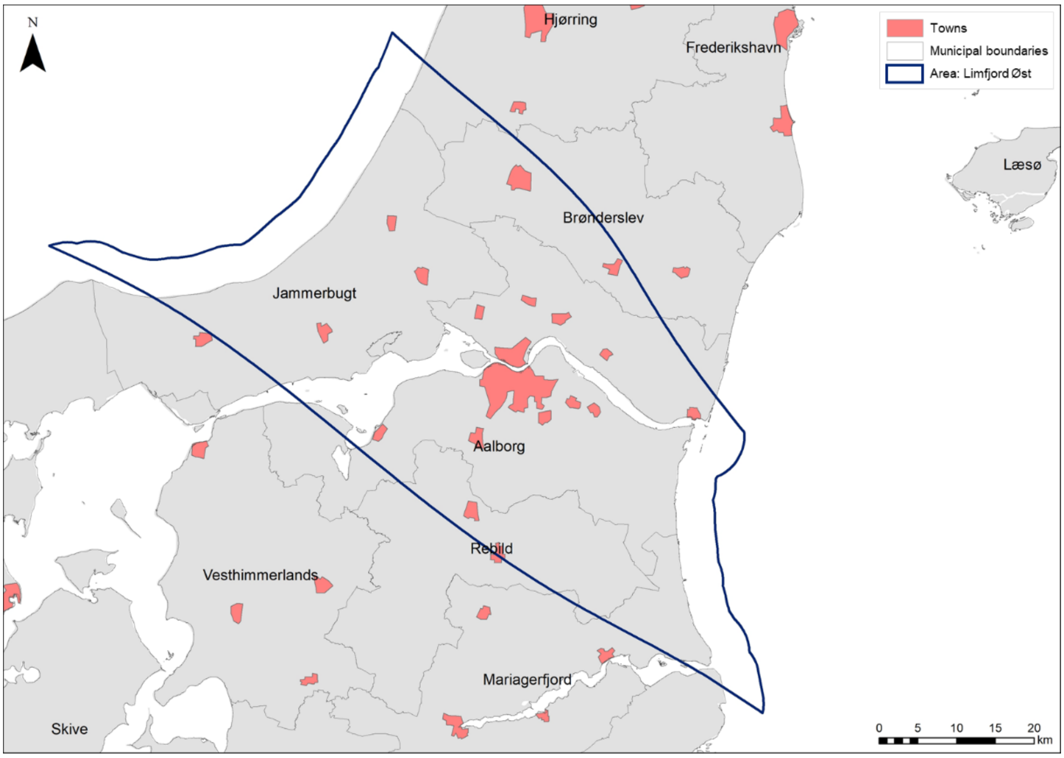


Figure 6.16. *Geographic outline of the Limfjord Øst area with municipal boundaries and towns indicated.*

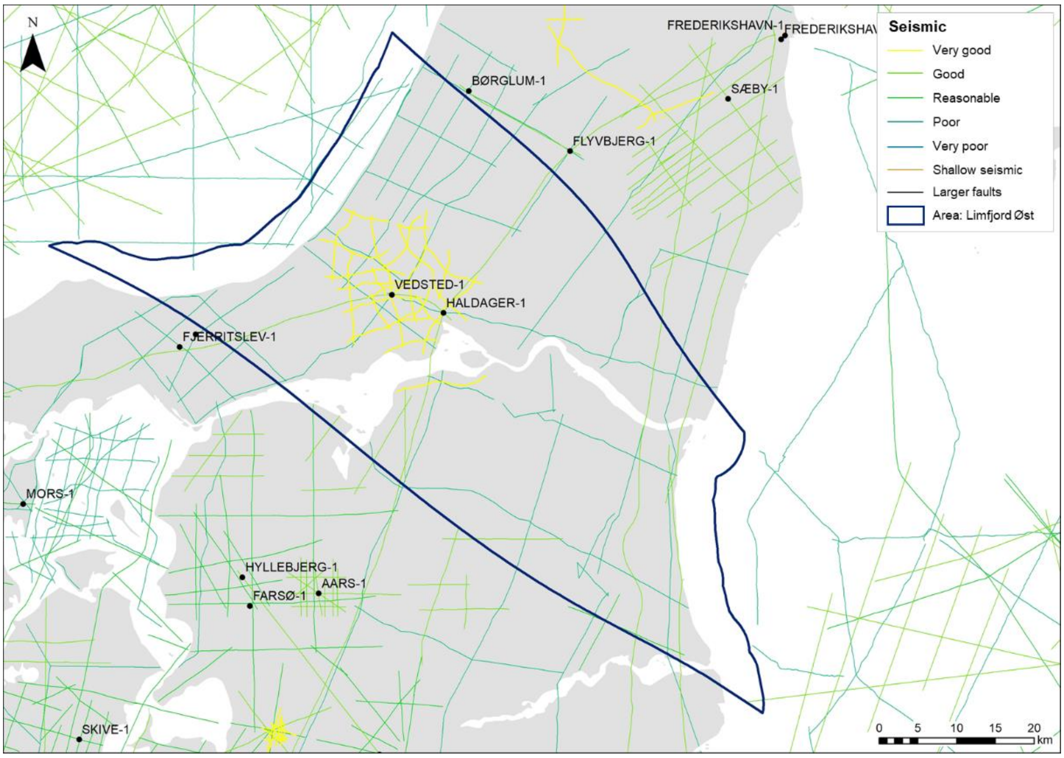


Figure 6.17. *Location map showing seismic lines and their quality, and deep boreholes in the Limfjord Øst area.*

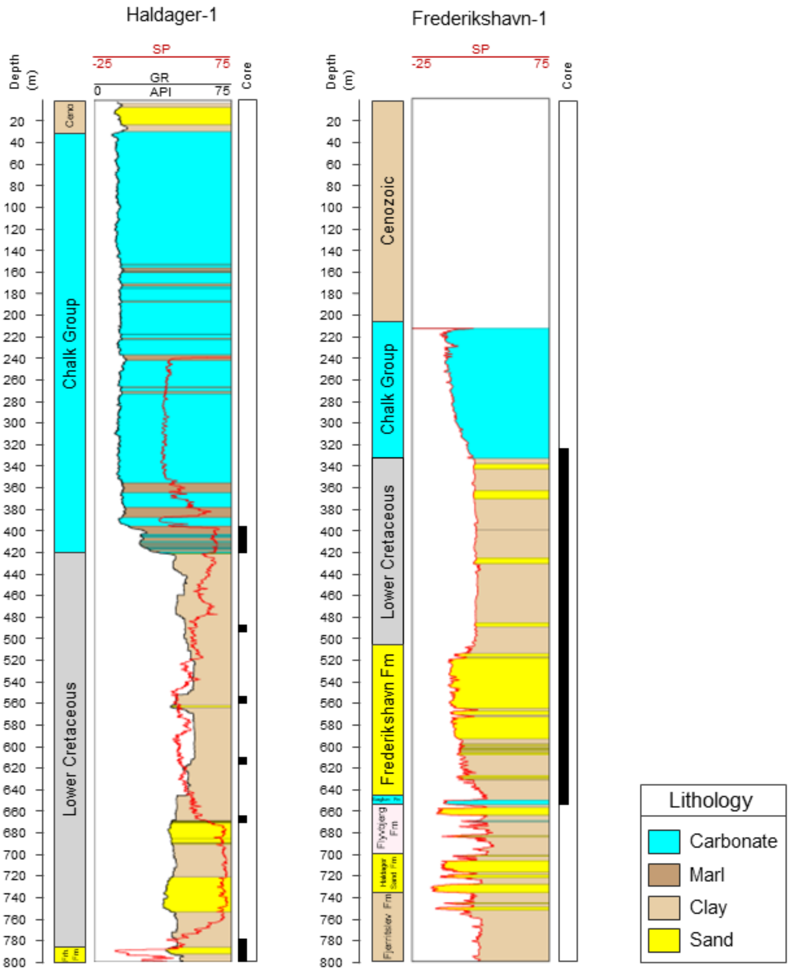


Figure 6.18. *Lithological logs based on petrophysical log interpretations of the 0–800 meters depth interval in the Haldager-1 (Limfjord Øst area) and Frederikshavn-1 (Nordjylland area) boreholes. In the Haldager-1 well log, carbonate constitutes the interval from approximately 40 meters to approximately 400 meters, and below is an interval of Lower Cretaceous clay with interbedded sand layers. From the well log interpretation, the Lower Cretaceous interval in Frederikshavn-1 is shown as dominated by clay. This is probably due to limited vertical resolution of the well logs, since numerous sand layers are recorded from the core description shown in Figure 6.4. Due to the lithological variations observed from cores of the clay dominated sections, they are not regarded as being lithologically homogenous. Figure 6.18 is identical to Figure 6.3, but due to its relevance for the Limfjord Øst area, it is presented here for the sake of completeness.*

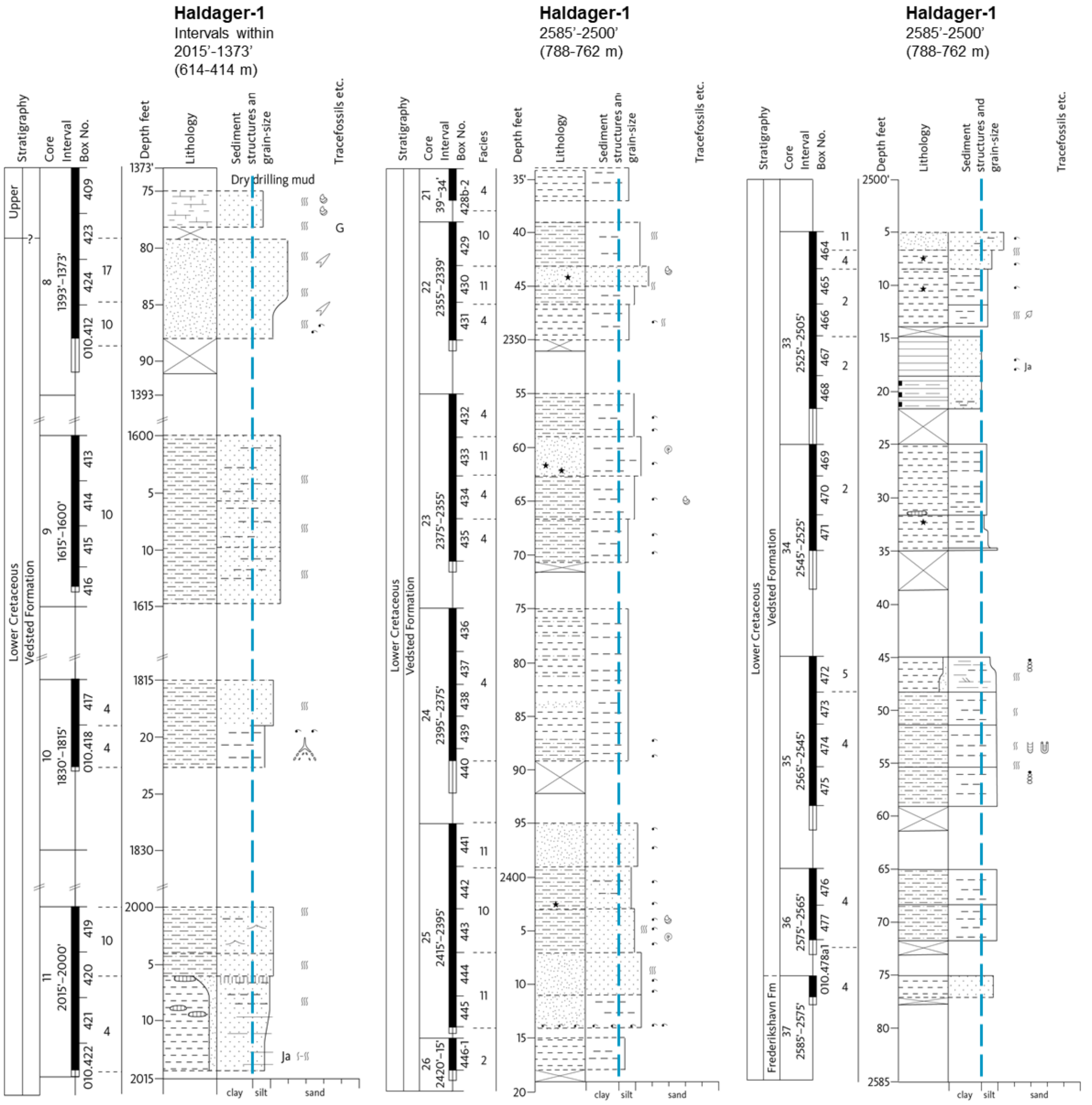


Figure 6.19. *Sedimentological log from representative sections of the Lower Cretaceous Vedsted Fm in the Haldager-1 well. The boundary between the clay and silt grain size is highlighted by the dotted blue line to emphasize the interbedding of clay layers and sediments of coarser grain sizes. The log sections illustrate that only a few, thin intervals are dominated by clay and that the sedimentary succession in general is not lithologically homogenous.*

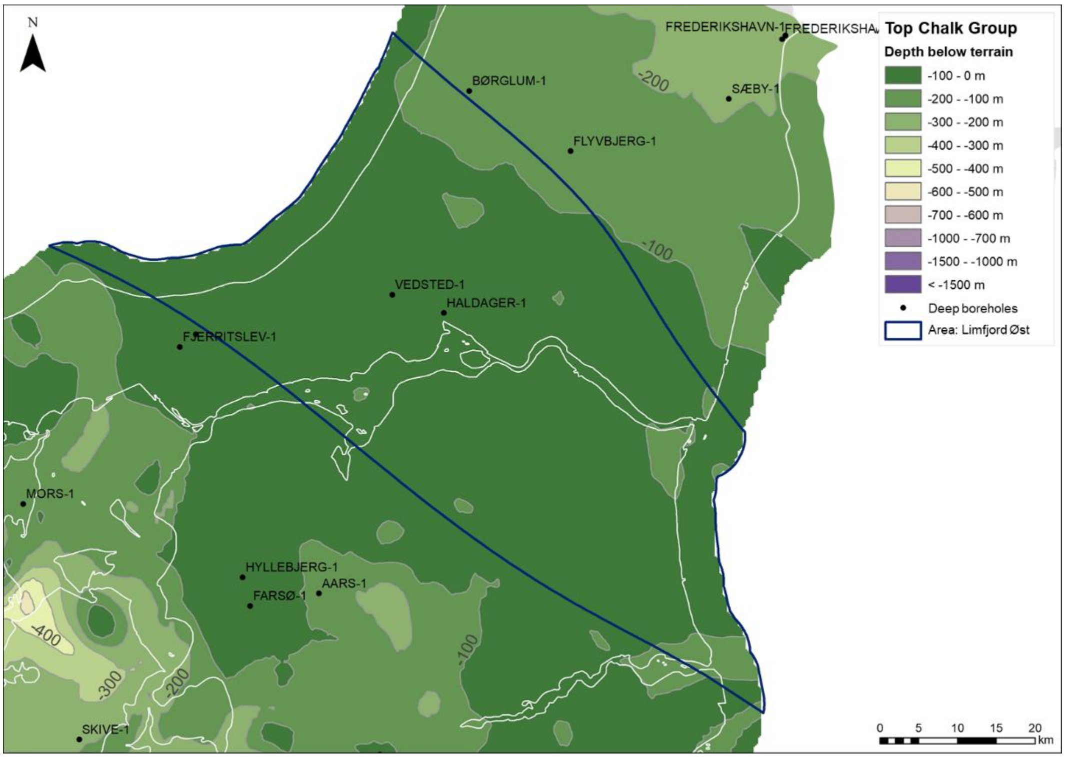


Figure 6.20. *Top Chalk Group depth map, Limfjord Øst area. The depth varies from 0 to 100 meters in the area.*

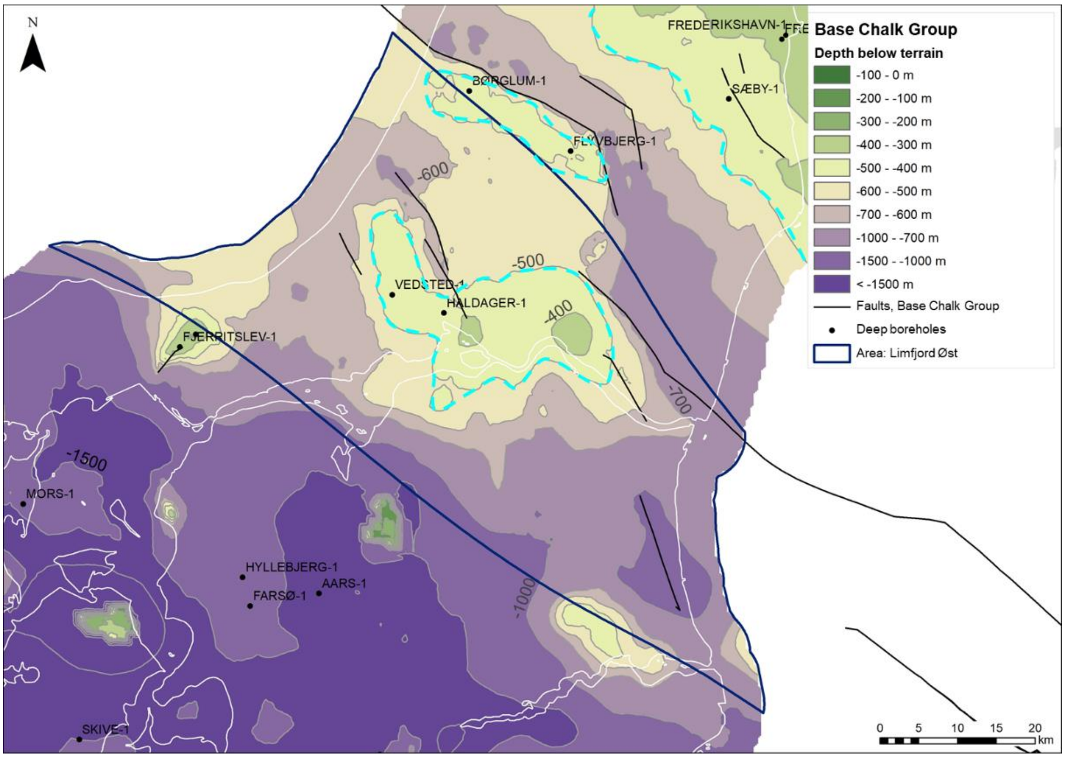


Figure 6.21. *Top Lower Cretaceous (base Chalk Group) depth map, Limfjord Øst area. Mapped faults intersecting the base of the Chalk Group are shown. The stippled blue line outlines areas where the top of the Lower Cretaceous occurs at depths between 300 and 500 meters.*

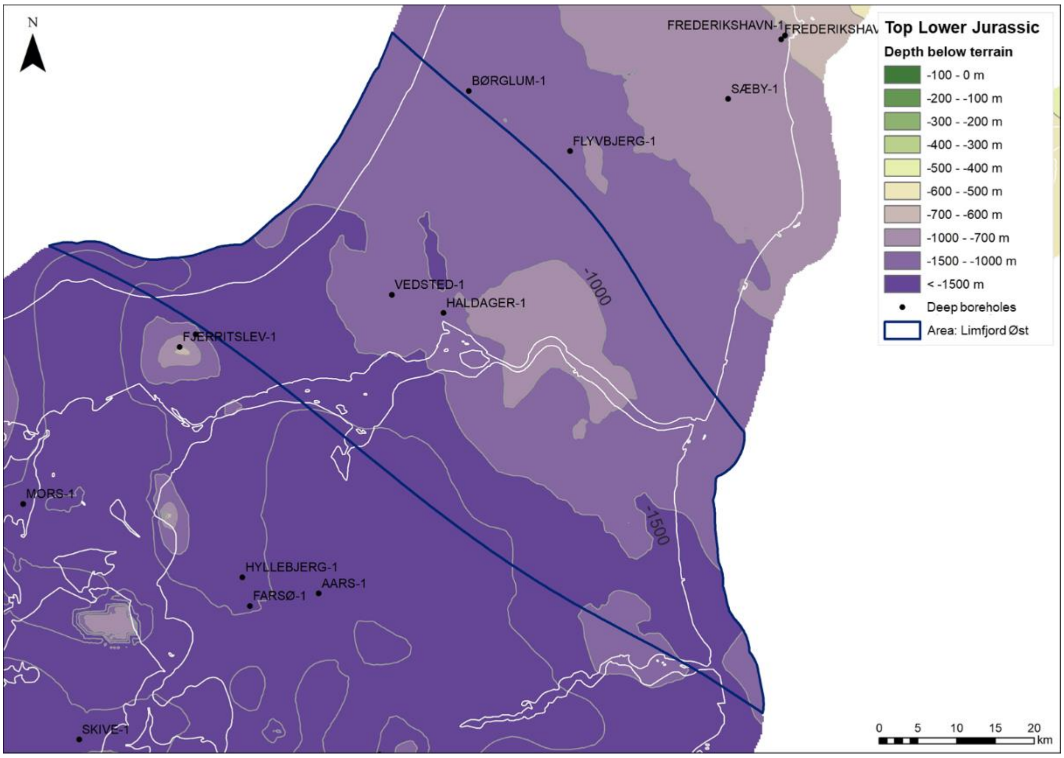


Figure 6.22. *Top Lower Jurassic depth map, Limfjord Øst area.*

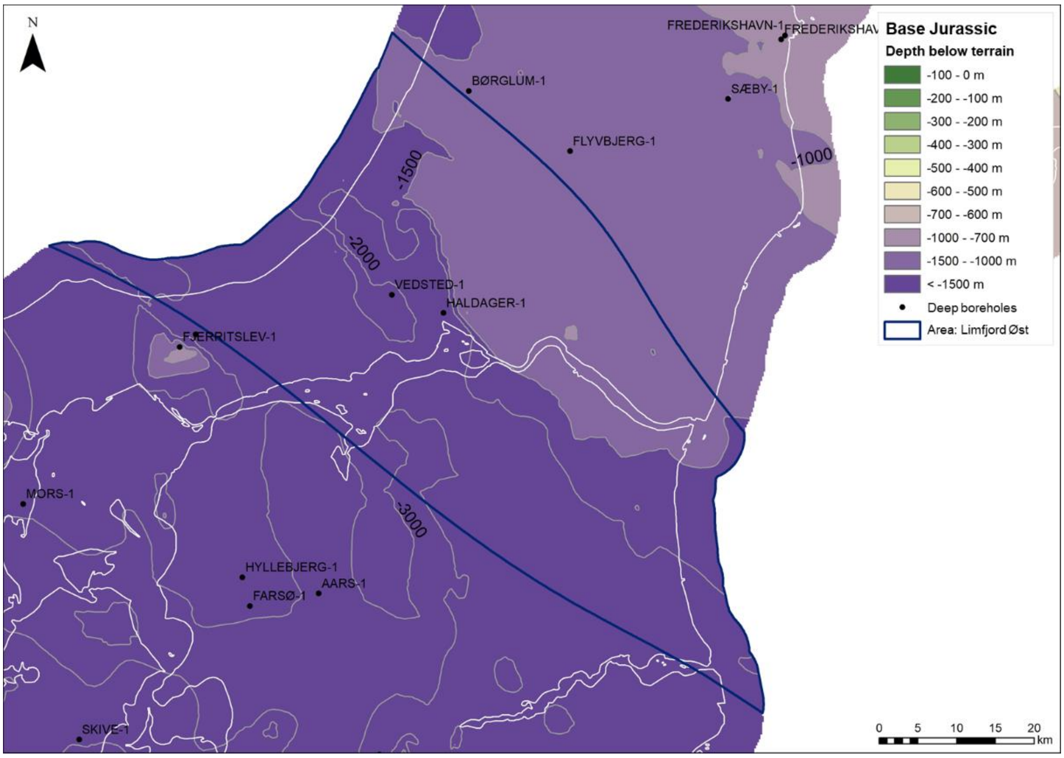


Figure 6.23. *Base Jurassic depth map, Limfjord Øst area. The base of the Jurassic occurs deeper than 1000 meters in the entire area.*

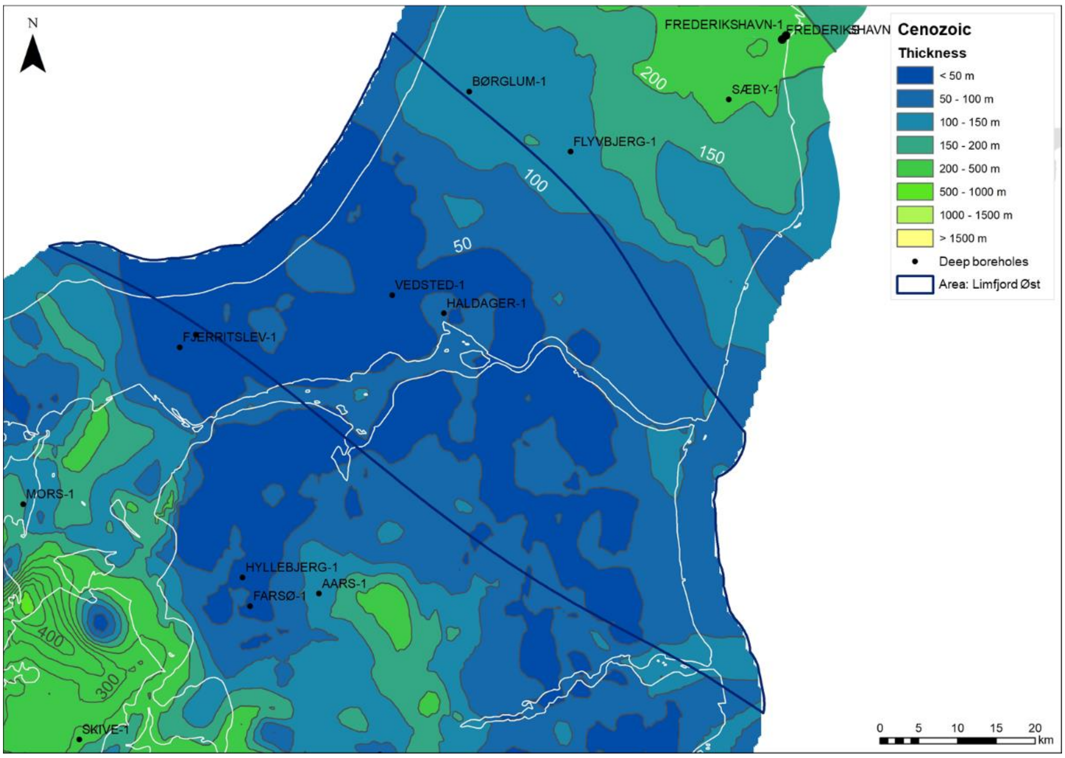


Figure 6.24. *Cenozoic thickness map, Limfjord Øst area. The Cenozoic sedimentary succession thickness varies between 0 and 100 meters.*

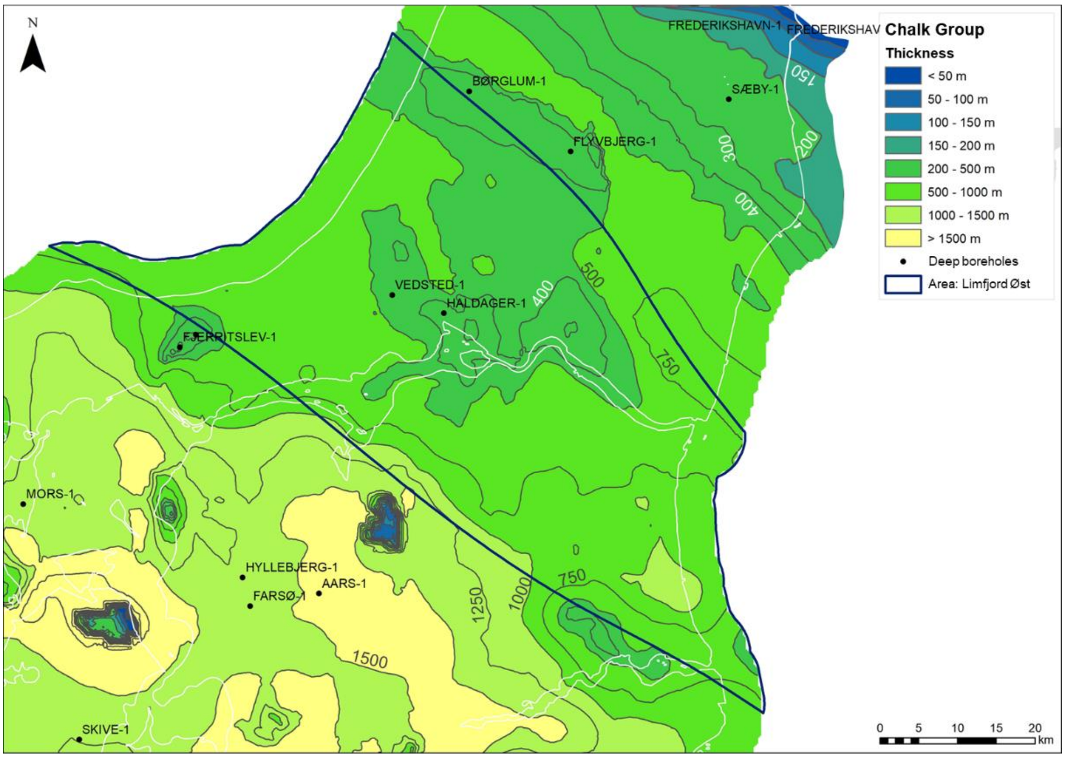


Figure 6.25. *Thickness map of the Chalk Group, Limfjord Øst area. The thickness is generally in the range of 400 to 750 meters.*

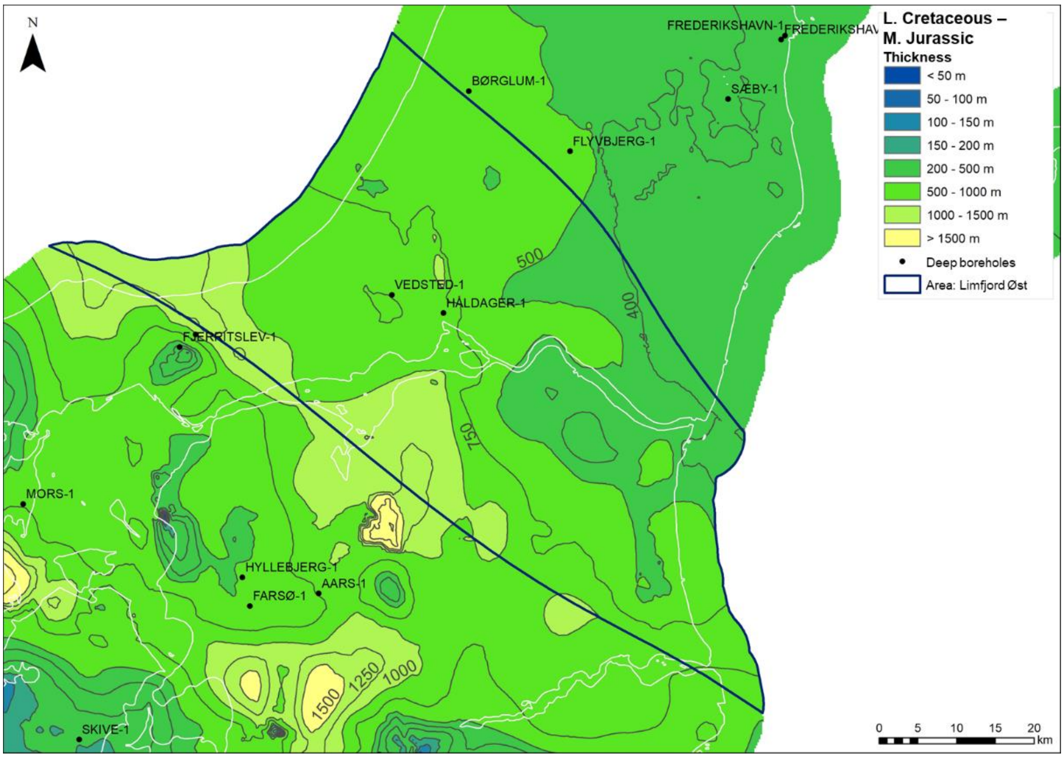


Figure 6.26. *Thickness map of the Lower Cretaceous to Middle Jurassic sections, Limfjord Øst area. The thickness varies from around 400 meters in the east to more than 1000 meters in the southwest (light green areas).*

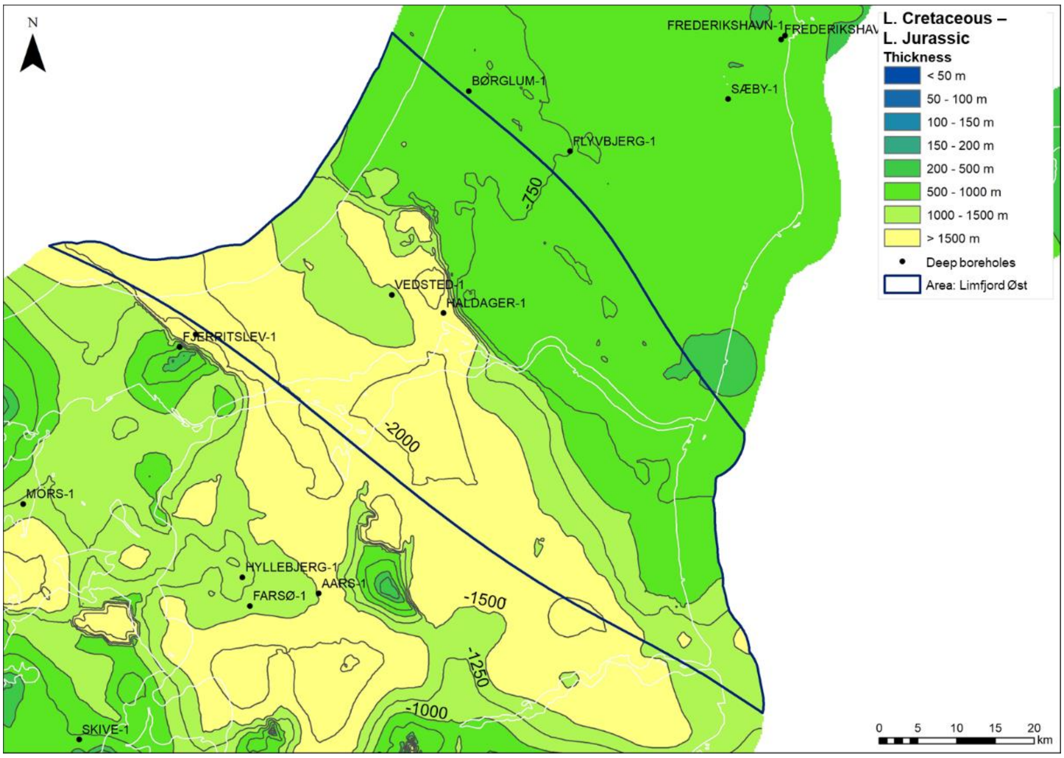


Figure 6.27. *Thickness map of the combined Lower Cretaceous and Jurassic sedimentary sections, Limfjord Øst. The thickness varies from 700 meters in the north and east to more than 1500 meters in the south and west. Locally, it exceeds 2000 meters.*

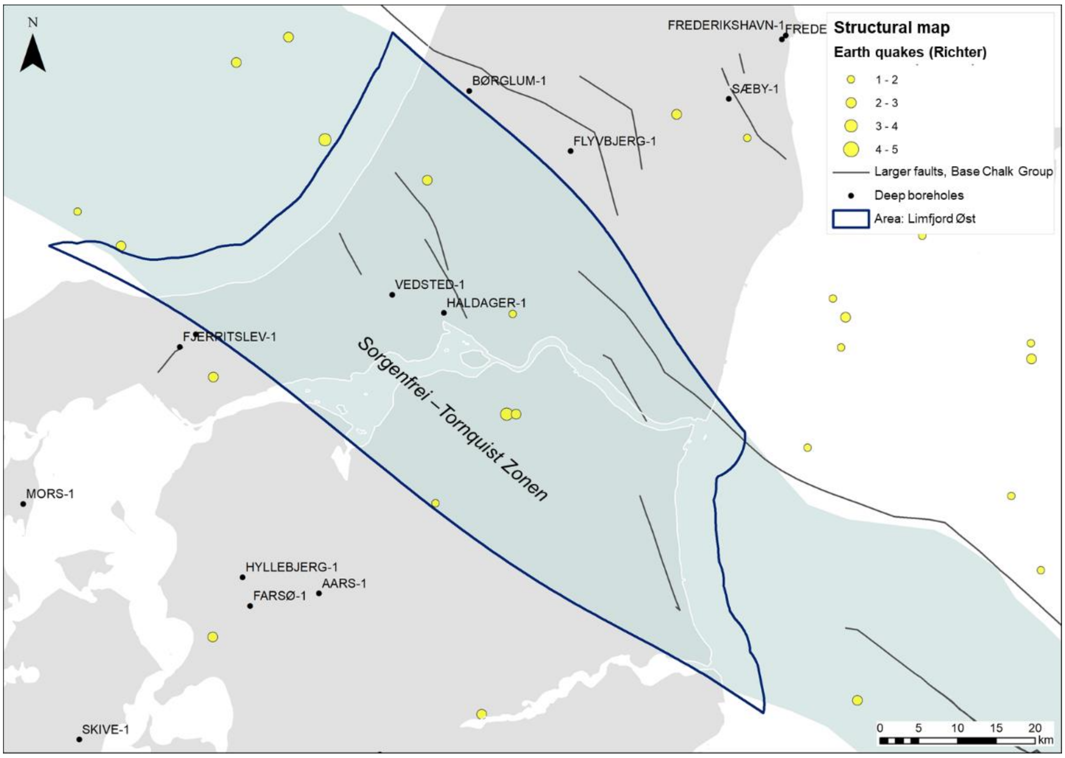


Figure 6.28. *Earthquakes registered during the past 50 years plotted on a structural map, Limfjord Øst area. The magnitude of the earthquakes varies between 1 and 3 on the Richter Scale.*

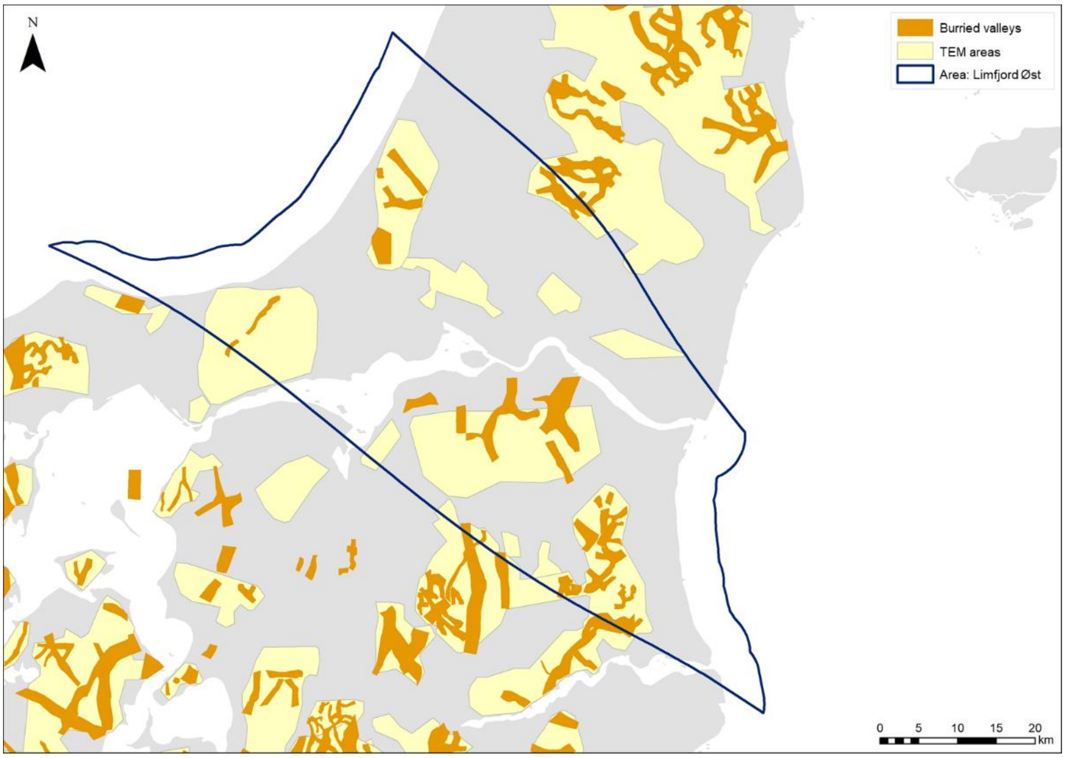


Figure 6.29. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Limfjord Øst area.*

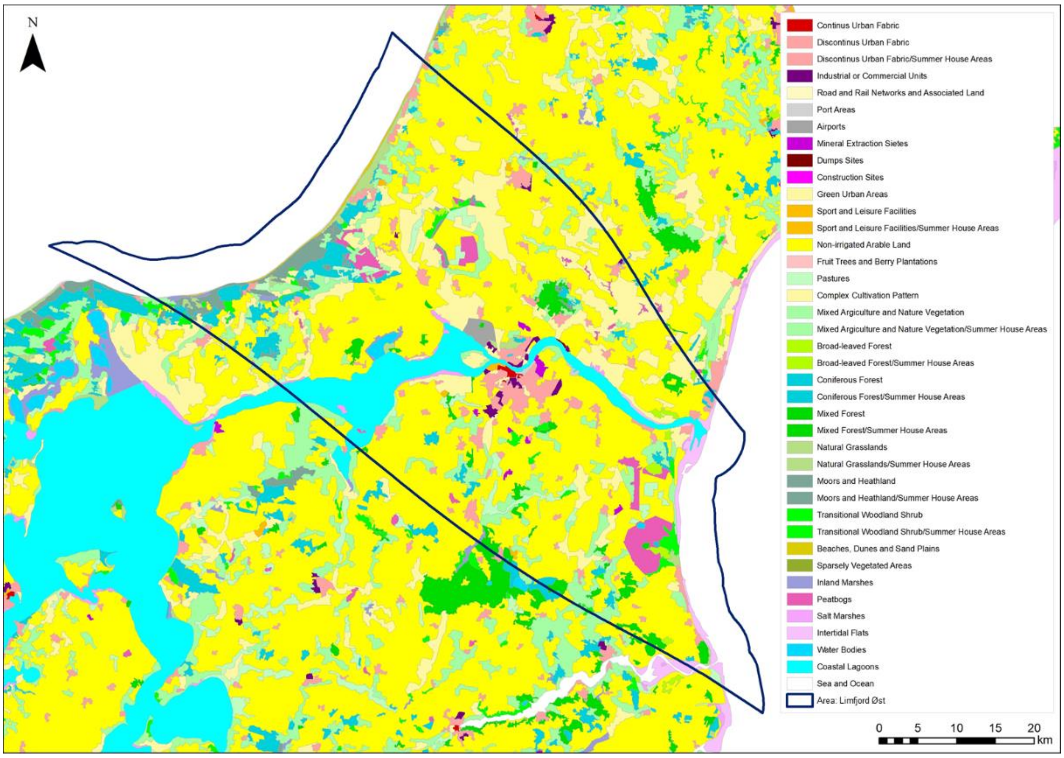


Figure 6.30. *Land use, Limfjord Øst area. The Limfjorden inlet extends across the area and is seen as the light blue areas on the map (MiljøGIS, 2021).*

6.3 Midt-Vestjylland

Carbonate constitutes the potential host rock, as the Chalk Group occurs extensively in the 400–500 meters depth interval in the eastern Midt-Vestjylland area. Top Chalk Group occurs at depths from 200 meters in the north to more than 500 meters to the south (Figure 6.34). Consequently, the top of the Chalk Group is too deep for it to provide a 250 meters thick barrier section as required by criterion 1.1 in most of the Midt-Vestjylland area, except for the northernmost part of the area.

The area is structurally complex with salt diapirs and salt ridges, and numerous faults intersect and off-set the sedimentary sections (Figures 4.14 and 4.15). As a result, the geological formations vary in thickness, depth, and dip over short distances (Figure 6.33), and the formations are generally of limited horizontal continuity. Thus, the spatial extent is generally less suitable in the area which results in an orange score for criterion no. 1.1.

The structural complexity of the area has also resulted in a less favourable score for criterion no. 4.1, related to the possibilities of reliable rock characterization from new data. The variations in depth, thickness and dip direction within short distances will be a challenge for the identification of sites where geological data on rock properties from new boreholes are representative for the entire investigation site of minimum 5x5 kilometers.

Criterion no. 4.3 addressing natural long term stability is scored as less suitable (orange) due to the presence of abundant salt structures in the area (Figure 4.15) and the associated risk of further salt remobilization in combination with the recorded seismic activity in the area (Figure 6.42).

As the Chalk Group in Midt-Vestjylland generally has a thickness of 500 to 1000 meters a carbonate barrier of the required thickness of 250 meters may be achieved in large parts of the area if disposal is considered at depths exceeding 500 meters (Figure 6.39).

Table 6.5. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Midt-Vestjylland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

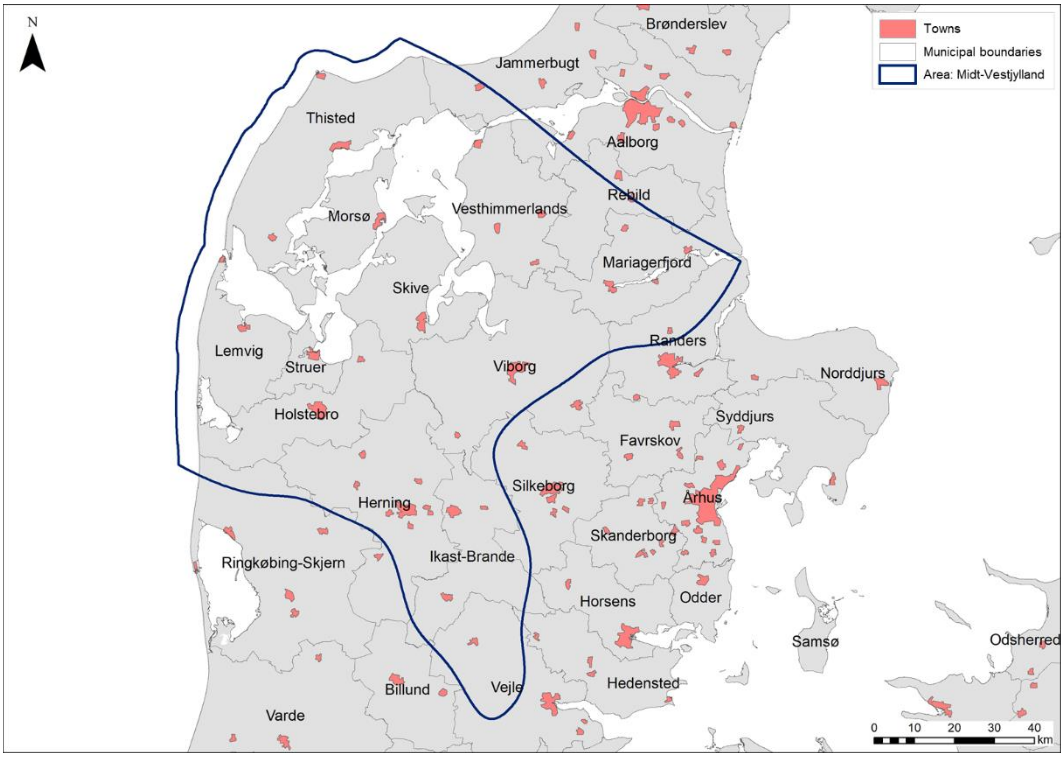


Figure 6.31. *Geographic outline of the Midt-Vestjylland area with municipal boundaries and towns indicated.*

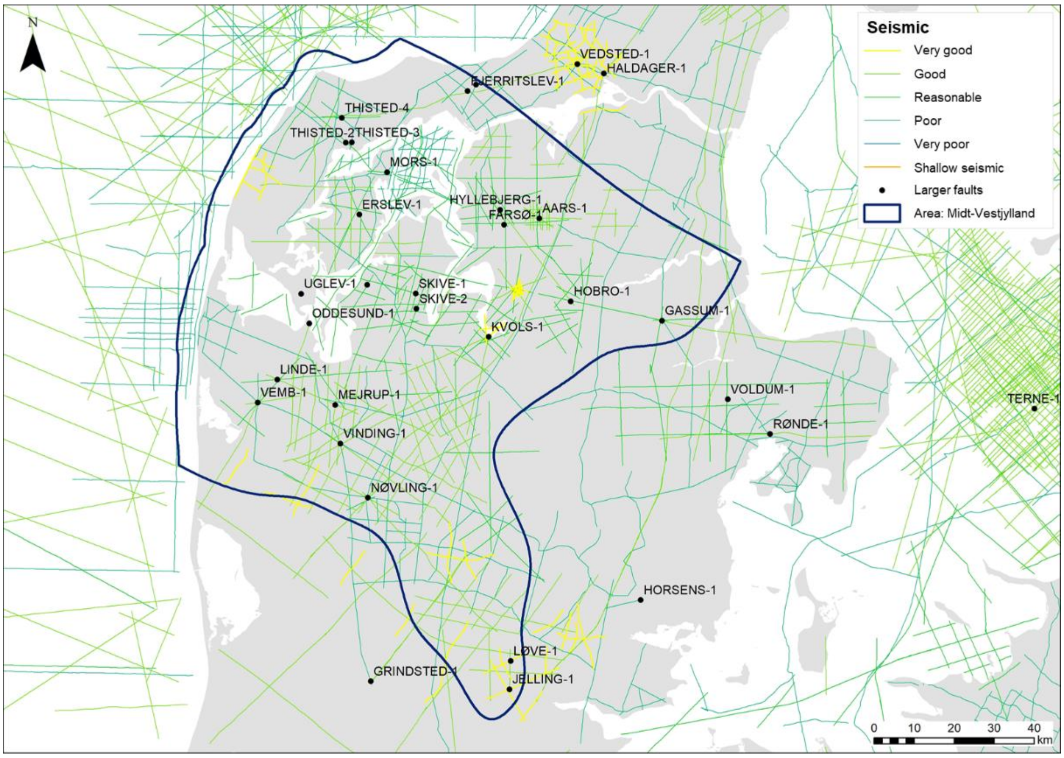


Figure 6.32. *Location map showing seismic lines and their quality, and deep boreholes in the Midt-Vestjylland area.*

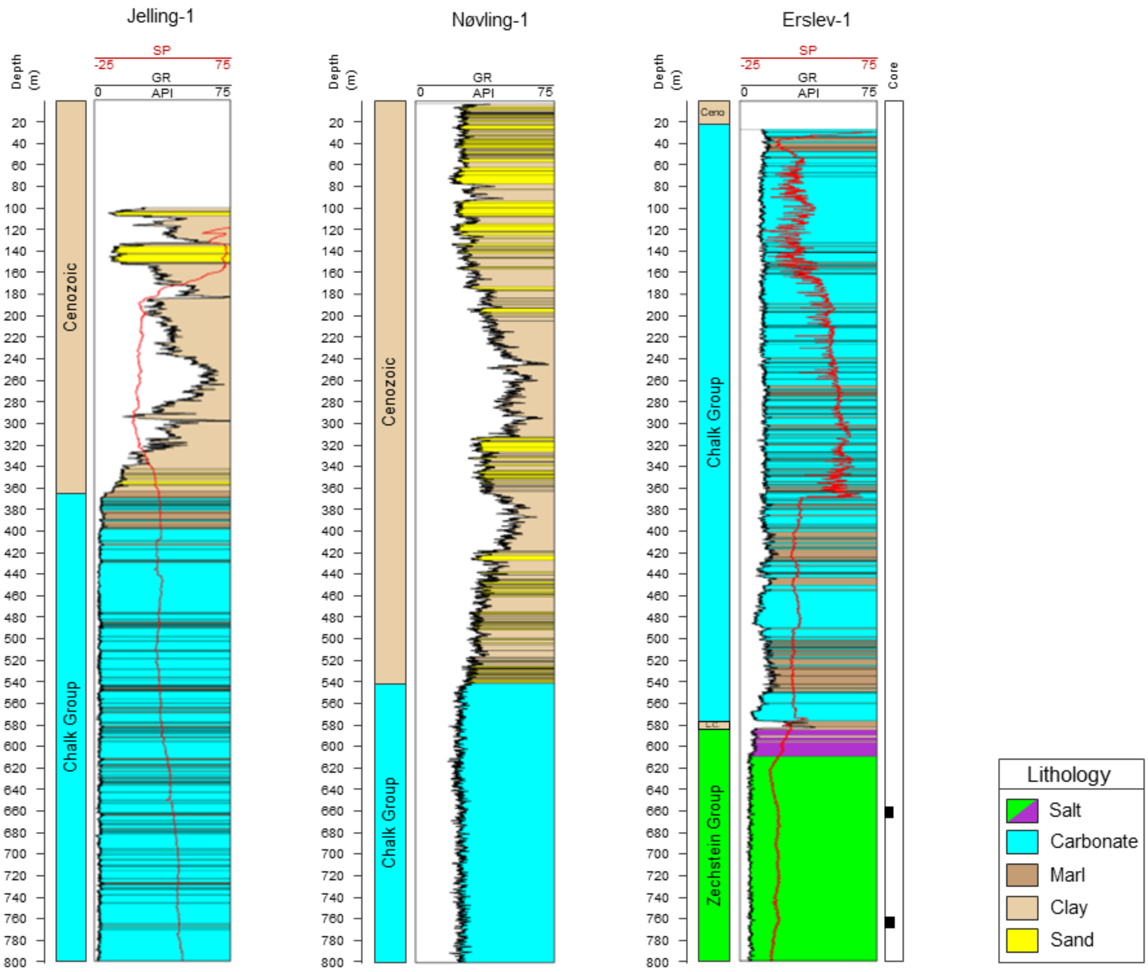


Figure 6.33. *Lithological well log interpretations of the 0 to 800 meters depth interval in the Jelling-1, Nøvling-1, and Erslev-1 wells. The logs illustrate that the rock types occurring at 500 meters depth vary from carbonate in Jelling-1 to a succession of interbedded clay and sand in Nøvling-1 to clay-rich carbonate (marl) in the Erslev-1 well.*

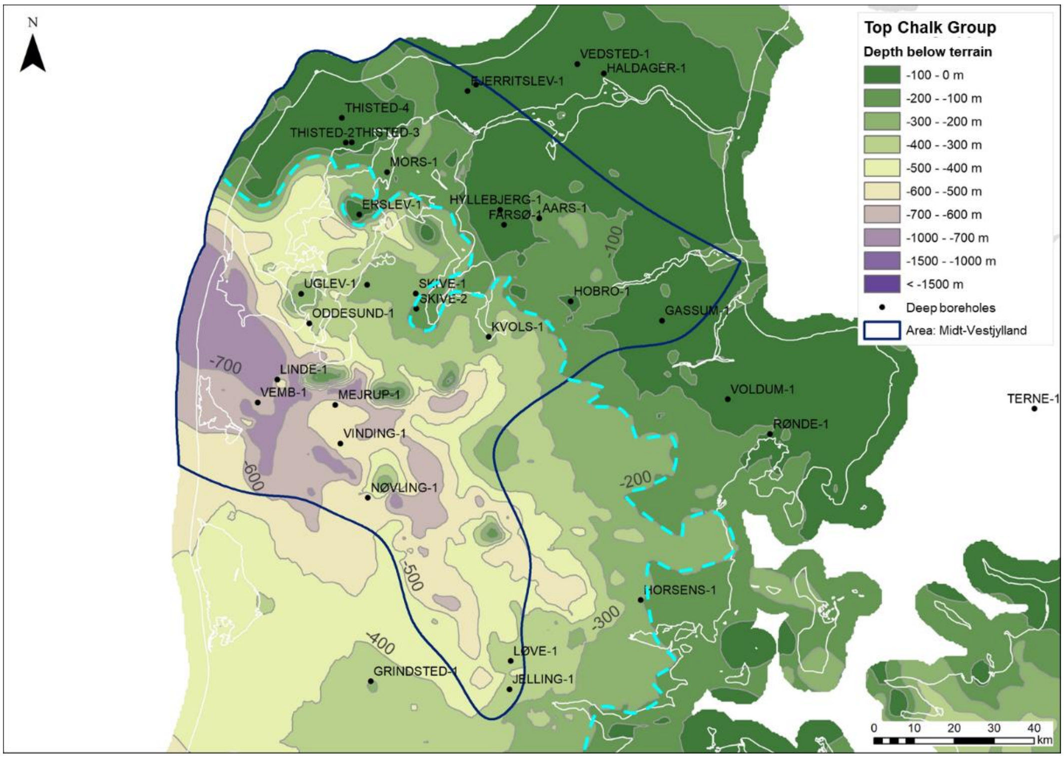


Figure 6.34. *Top Chalk Group depth map, Midt-Vestjylland area. The dotted line highlights the 200 meters depth contour. To the north and east the top of the Chalk Group is shallower than 200 meters whereas, to the south and west it is deeper, locally exceeding 700 meters.*

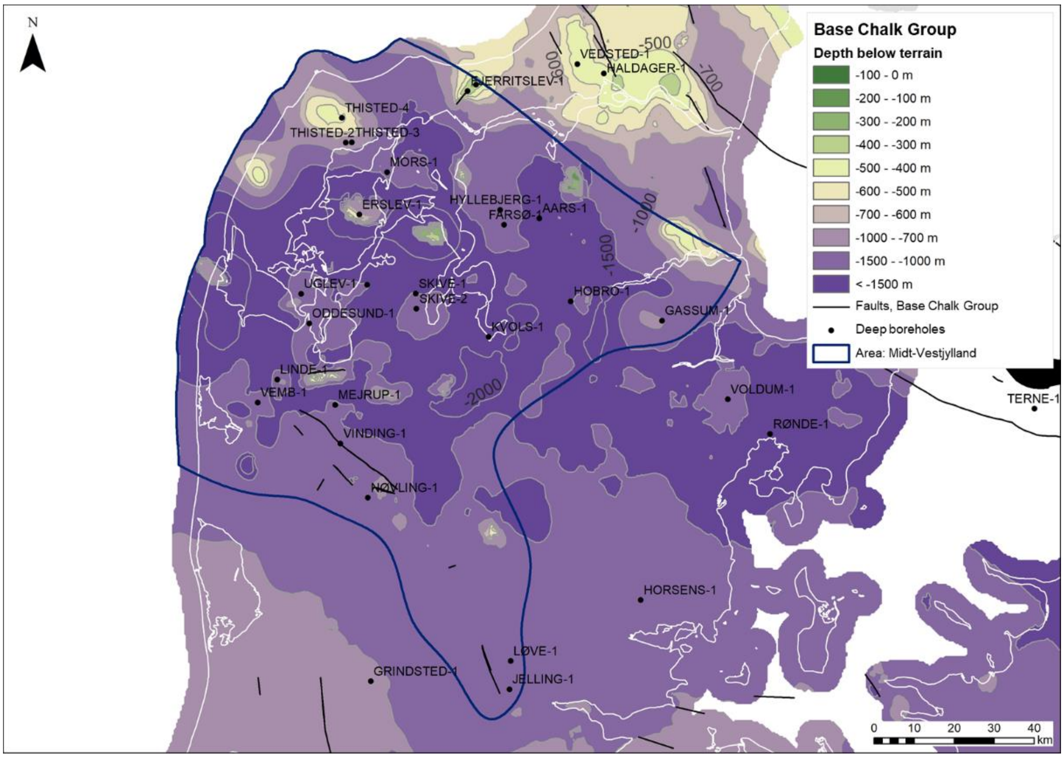


Figure 6.35. *Top Lower Cretaceous (the base of the Chalk Group) depth map, Midt-Vestjylland area. The irregular contours result from remobilized salt. Mapped major faults intersecting the base of the Chalk Group are shown.*

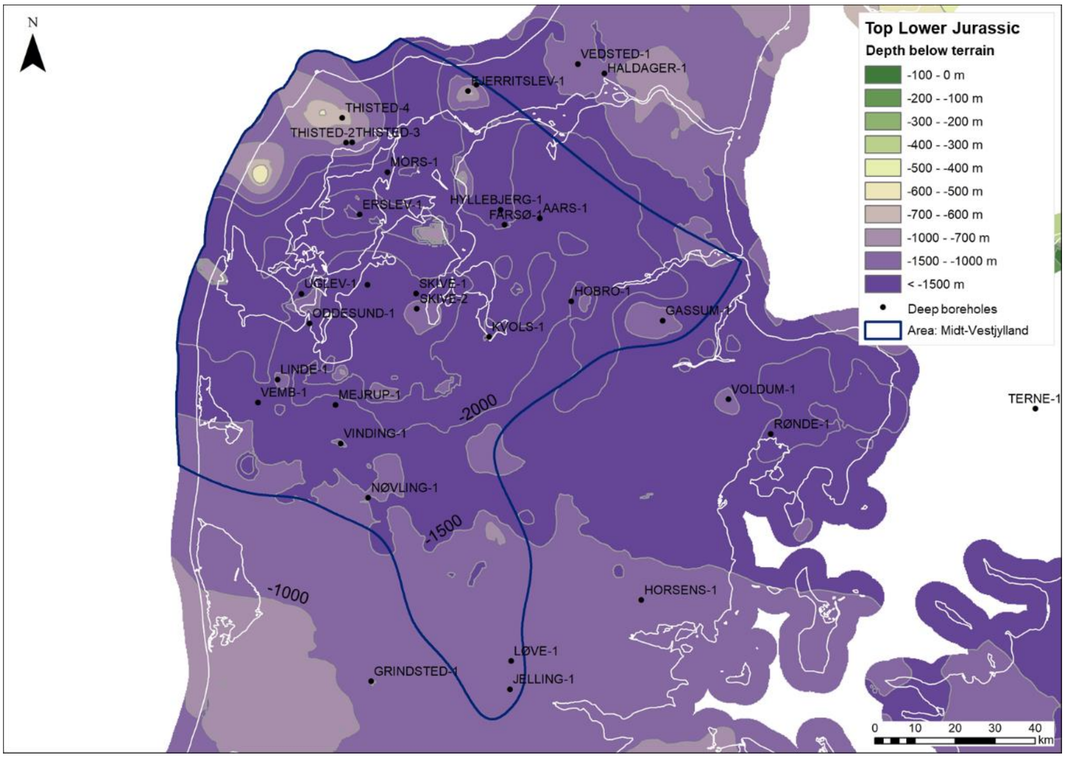


Figure 6.36. *Top Lower Jurassic depth map, Midt-Vestjylland area. The depth to top Lower Jurassic is generally more than 1500 meters, and the irregularity of the contours is due to the presence of salt.*

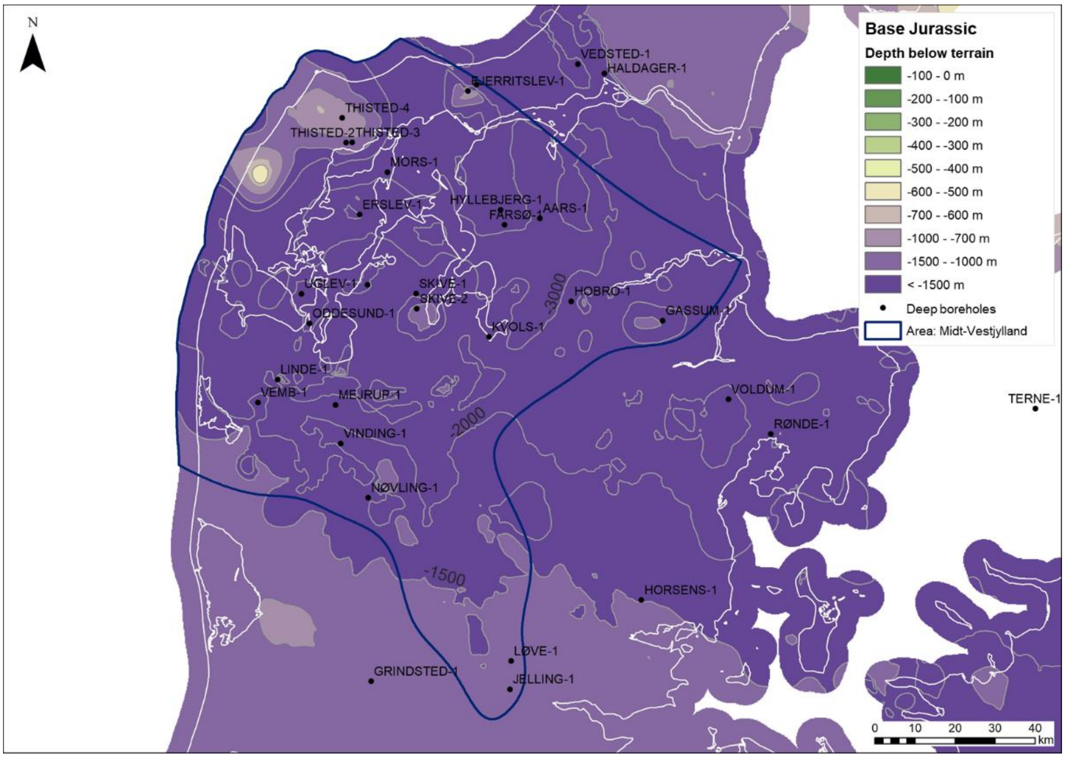


Figure 6.37. *Depth map of the base of the Jurassic, Midt-Vestjylland. The map illustrates that the base of the Jurassic generally occurs deeper than 1500 meters, locally deeper than 3000 meters.*

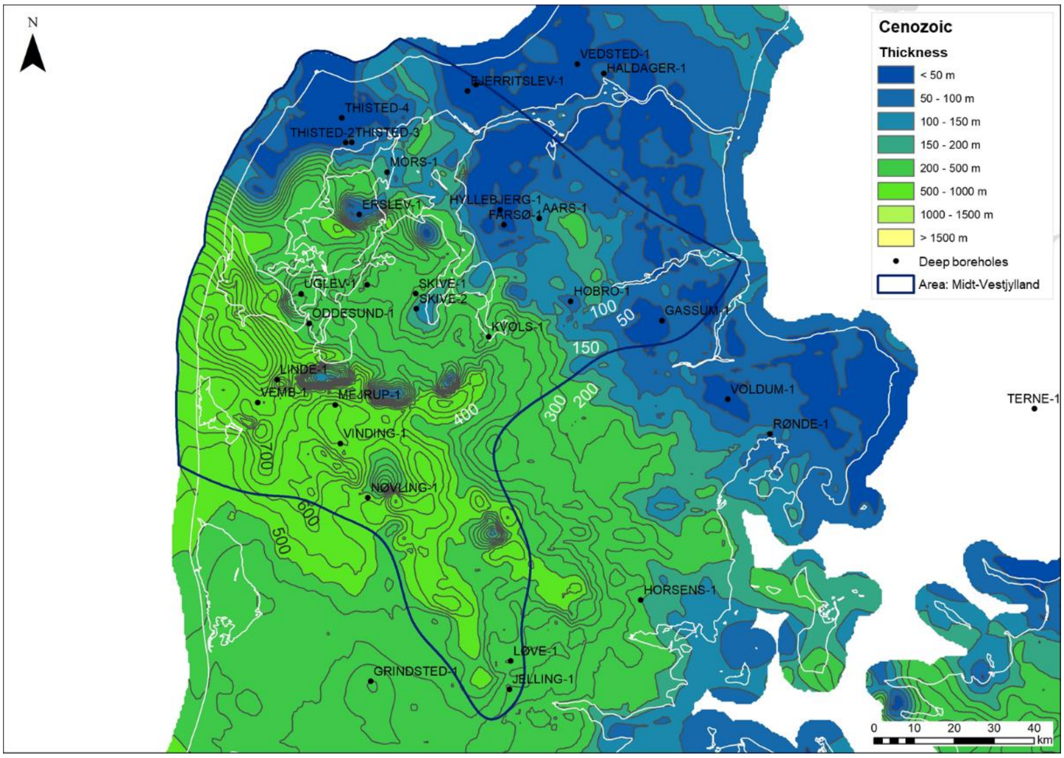


Figure 6.38. *Cenozoic thickness map, Midt-Vestjylland area. In large parts of the area, the Cenozoic succession is more than 200 meters thick and locally it exceeds 700 meters.*

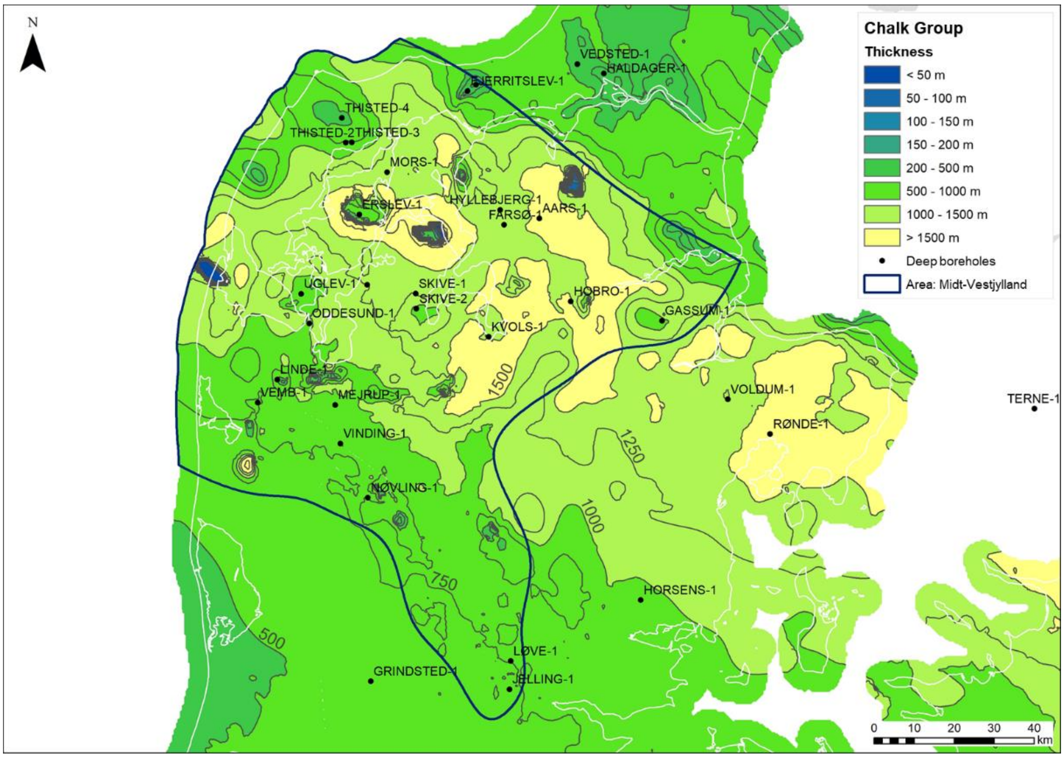


Figure 6.39. *Chalk Group thickness map, Midt-Vestjylland area. The carbonate thickness varies from 700 to 1500 meters over short distances as indicated by the irregularity of the depth contours. This is caused by remobilization of salt into salt diapirs and pillows.*

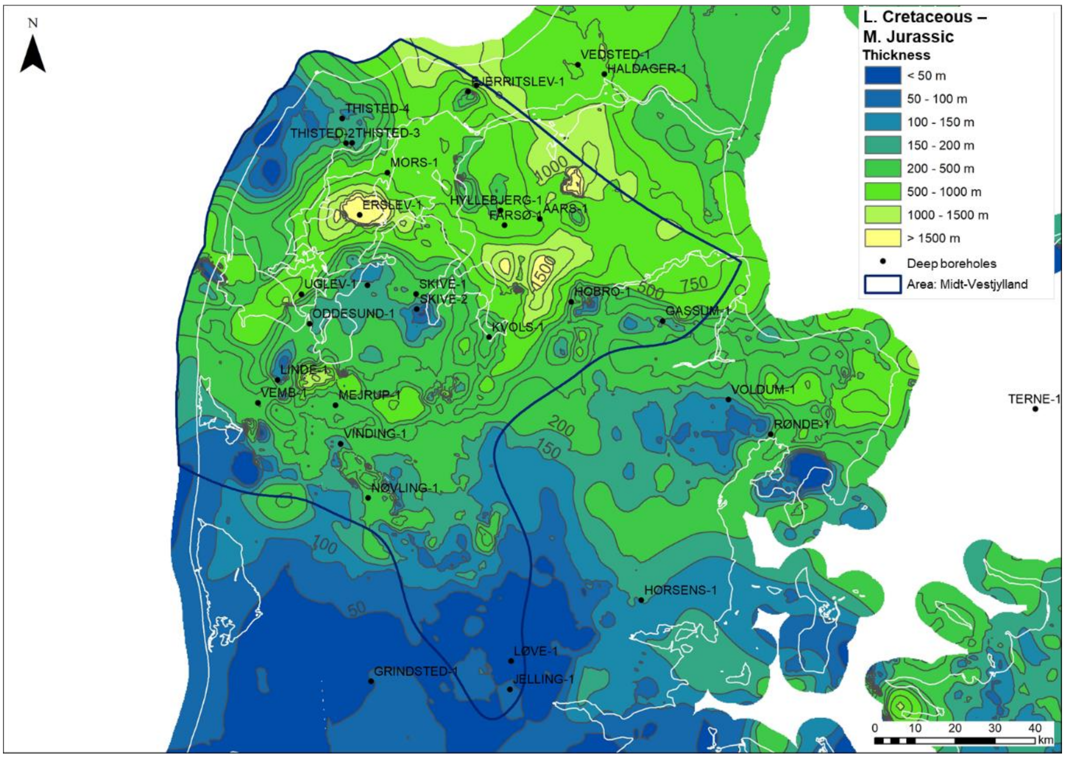


Figure 6.40. *Thickness map of the Lower Cretaceous to Middle Jurassic succession, Midt-Vestjylland area. The thickness varies from 50 meters (blue areas) to more than 1500 meters (yellow areas) over short distances due to the presence of underlying salt pillows and diapirs.*

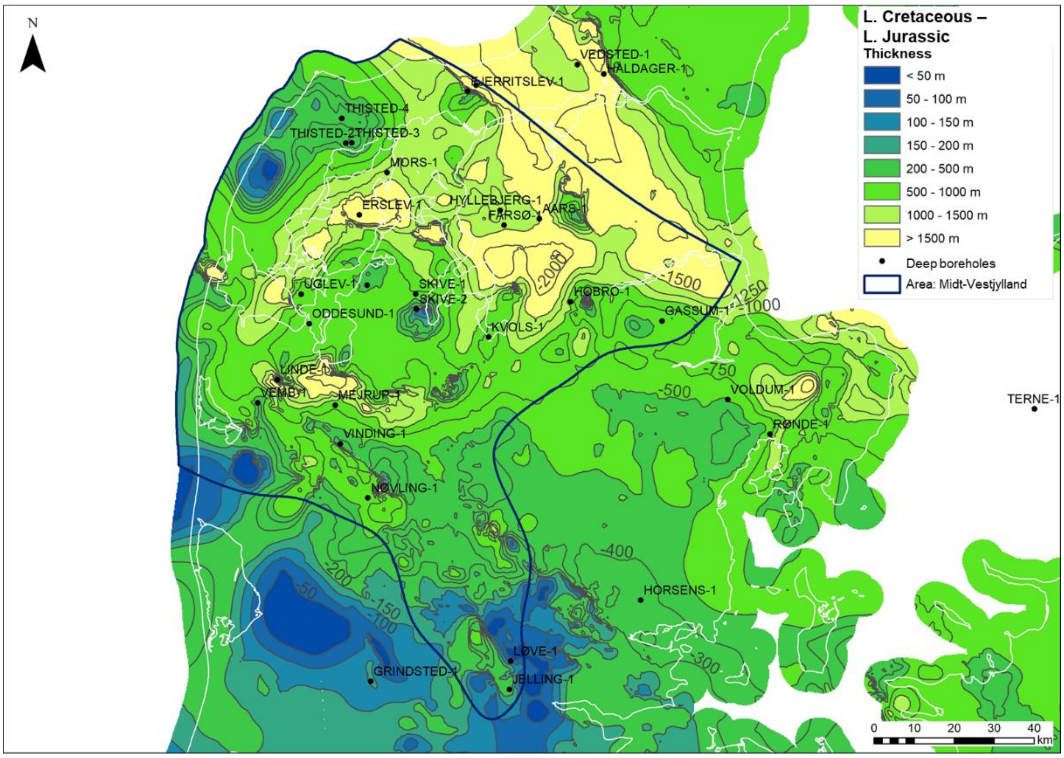


Figure 6.41. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Midt-Vestjylland area.*

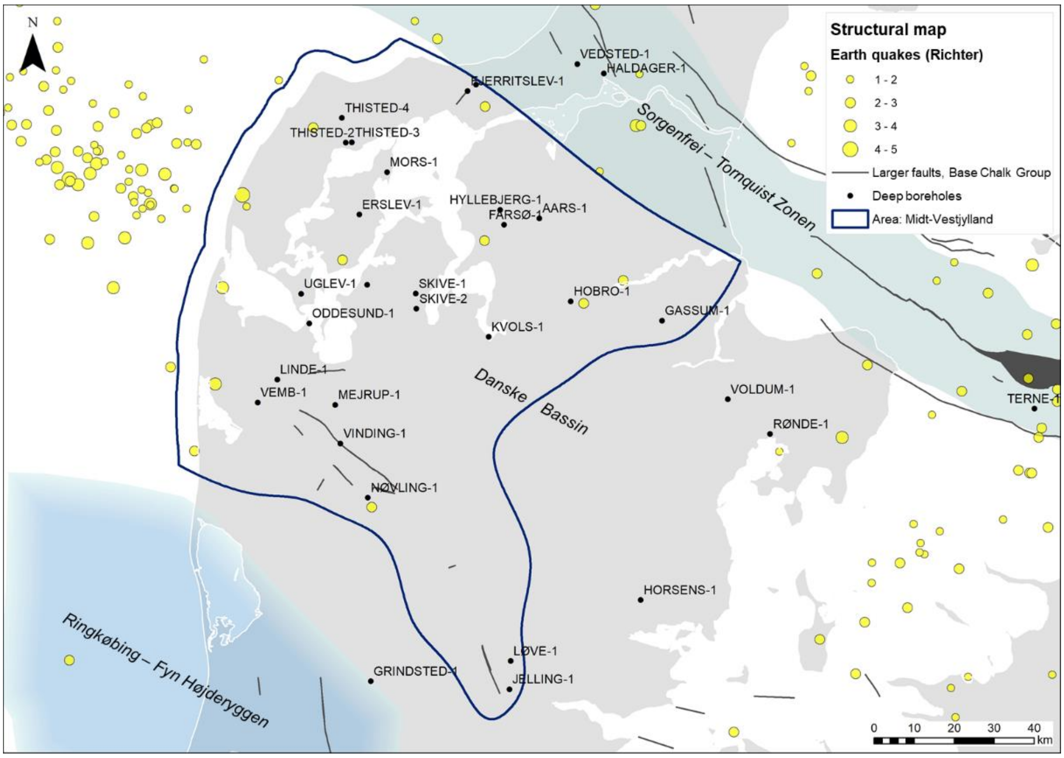


Figure 6.42. *Earthquakes registered during the past 50 years plotted on a structural map, Midt-Vestjylland area. In the offshore area to the west there is a high density of registered earthquakes with magnitudes from 1 to 4 (Richter scale).*

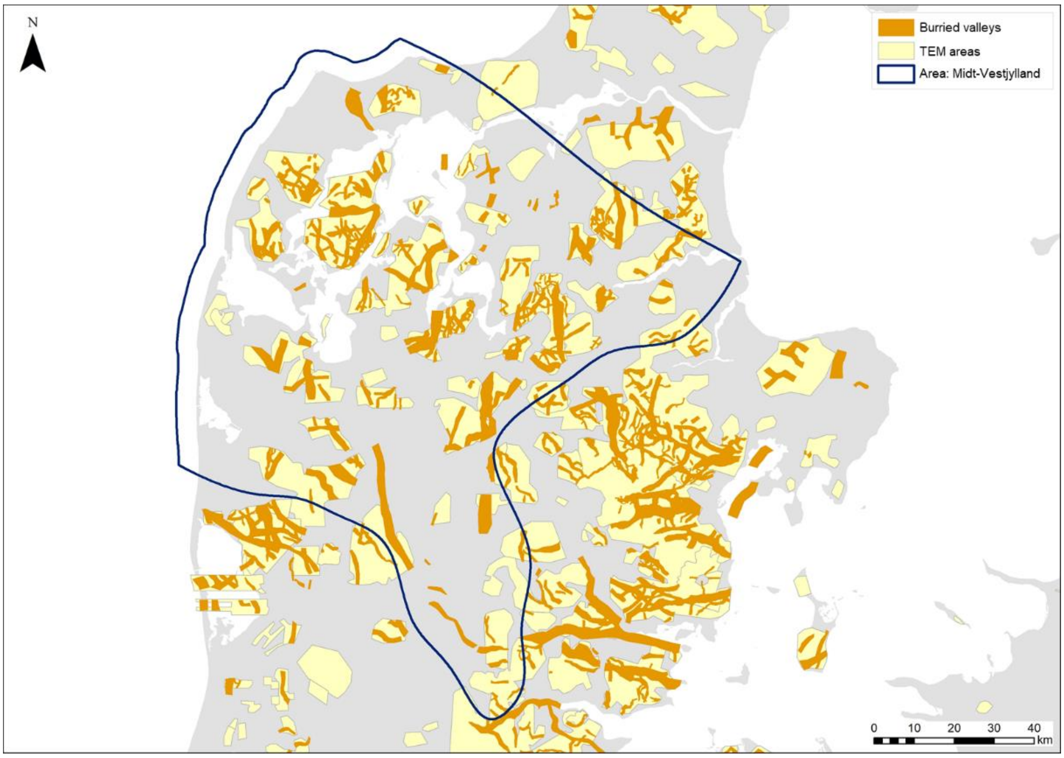


Figure 6.43. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Midt-Vestjylland area.*

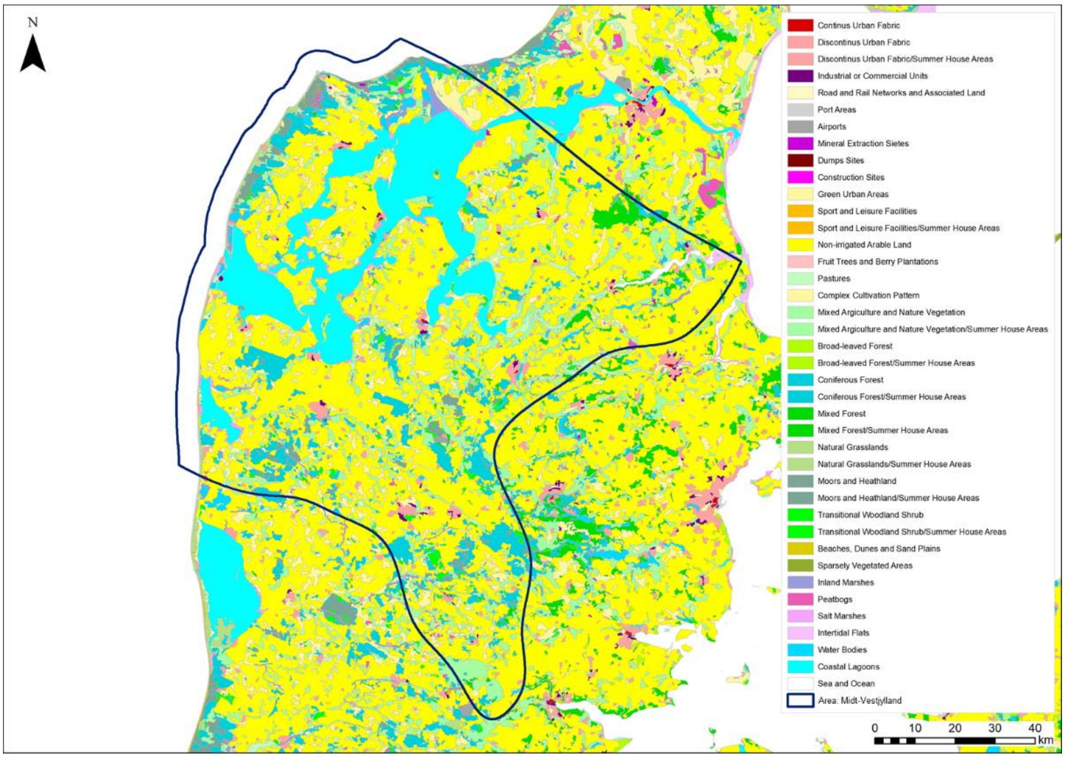


Figure 6.44. *Land use, Midt-Vestjylland. The light blue colour shows the presence of fiords and lakes including the Limfjorden inlet. (MiljøGIS, 2021).*

6.4 Østjylland

Carbonates constitute the potential host rock in the Østjylland area and occur in the 400 to 500 meters depth interval throughout the entire area. Carbonate also forms the barrier rock and in the eastern part of the area carbonate rock is locally present at ground level. The top of the Chalk Group occurs at increasing depths towards the southwest, where it is as deep as 300–400 meters, and the base of the Chalk Group occurs at 1000 meters depth or deeper (Figures 4.16, 4.17, 6.47, 6.48 and 6.49). Criterion no. 1.1 has been scored as favourable (green) since the carbonate section has a thickness of 250 meters in the ECZ in addition to the presence in the 400–500 meters depth interval in most of the area. However, in the southwestern part of the area, the carbonate is not sufficiently thick to form a 250 meters barrier in the ECZ.

As the Chalk Group thickness in the Østjylland area is generally 1000 meters or more, a carbonate barrier of the required thickness of 250 meters is achieved also in the western parts of the area if disposal is considered at depths exceeding 500 meters (Figure 6.53). In this situation the requirement for the total thickness of host and barrier rocks can be fulfilled.

Table 6.6. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Østjylland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

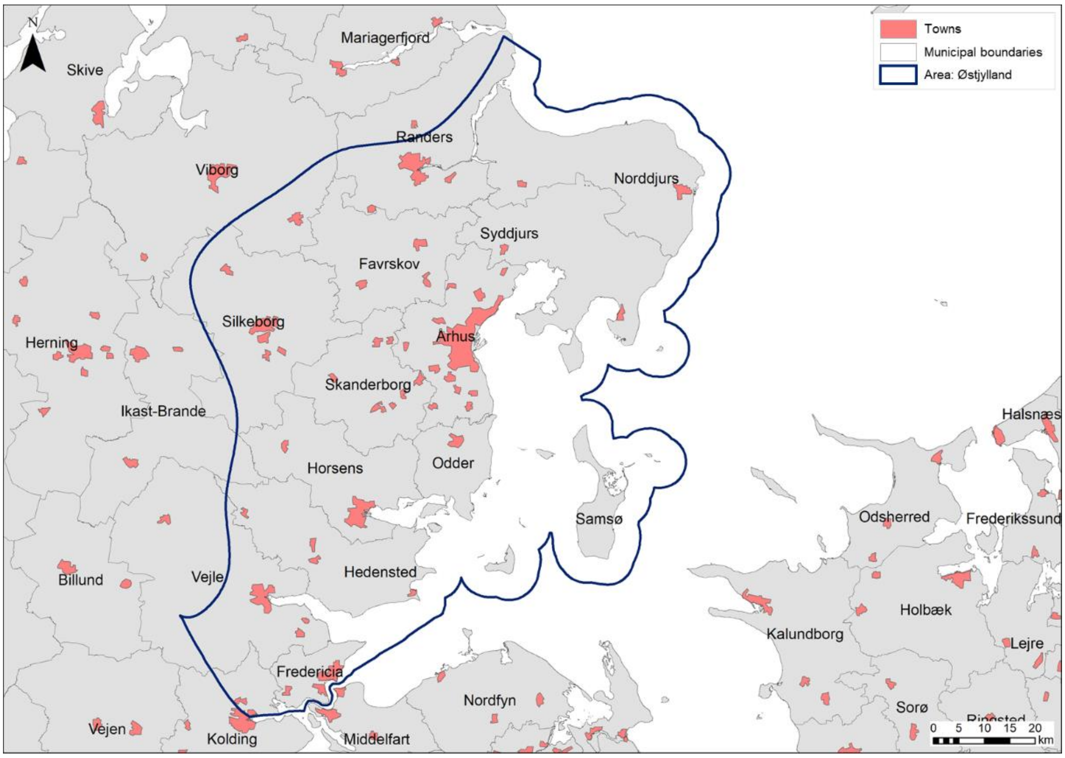


Figure 6.45. *Geographic outline of the Østjylland area with towns and municipal boundaries indicated.*

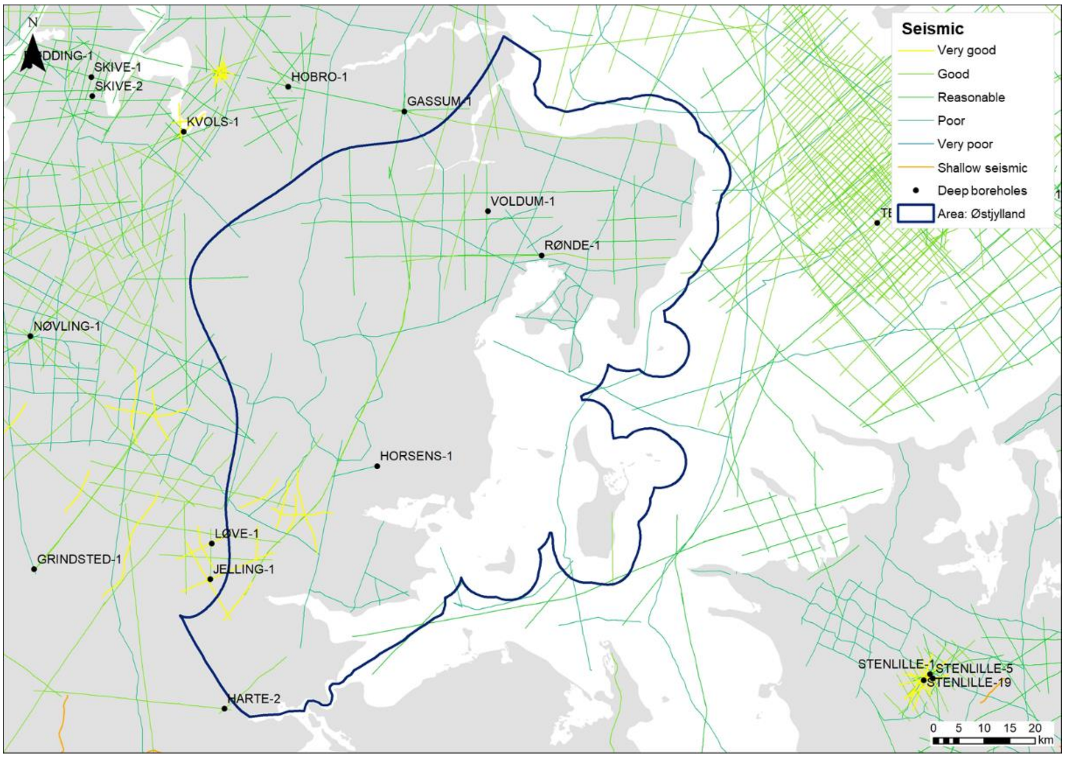


Figure 6.46. *Location map showing seismic lines and their quality, and deep boreholes in the Østjylland area.*

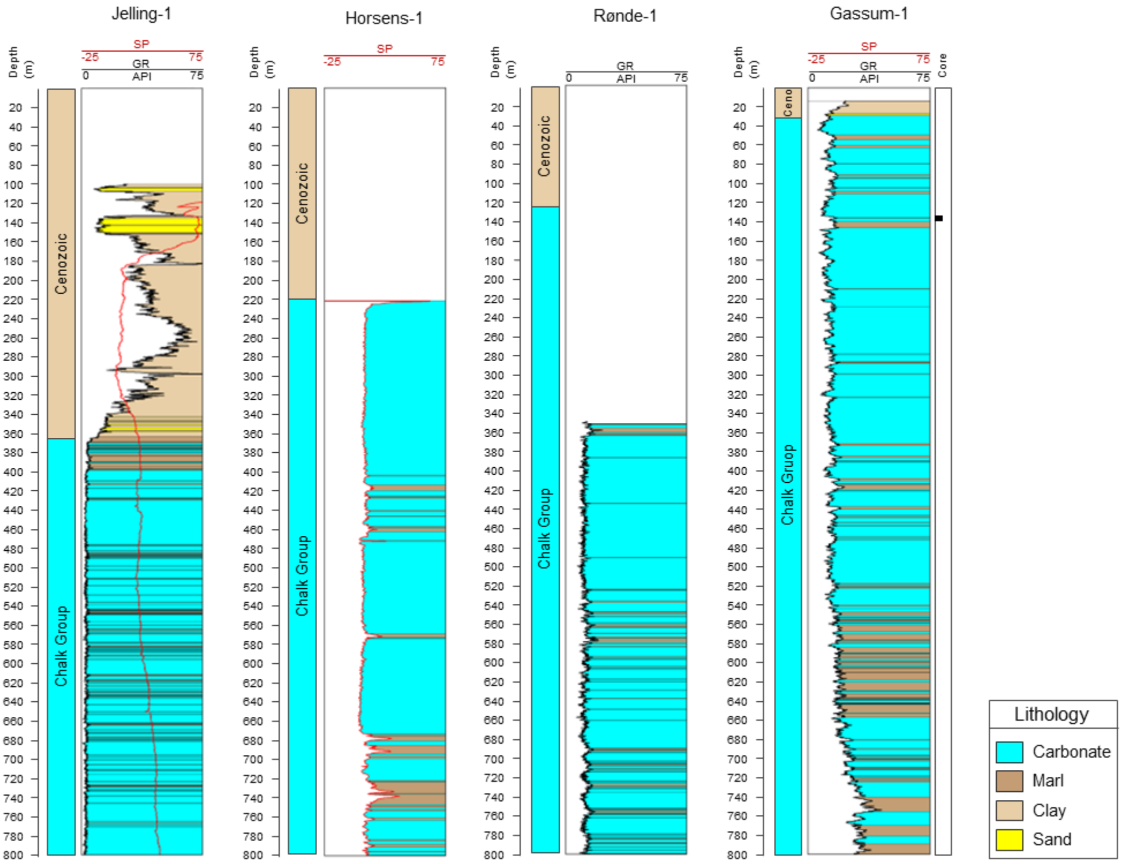


Figure 6.47. *Lithological log interpretations of the 0–800 meters depth interval illustrating how the top of the Chalk Group occurs at depths increasing from 30 meters in the Gassum-1 well in the north (right part of the well log panel) to approximately 360 meters in the Jelling-1 well in the south. Further, the figure shows that carbonates in the Chalk Group comprise numerous layers of marl.*

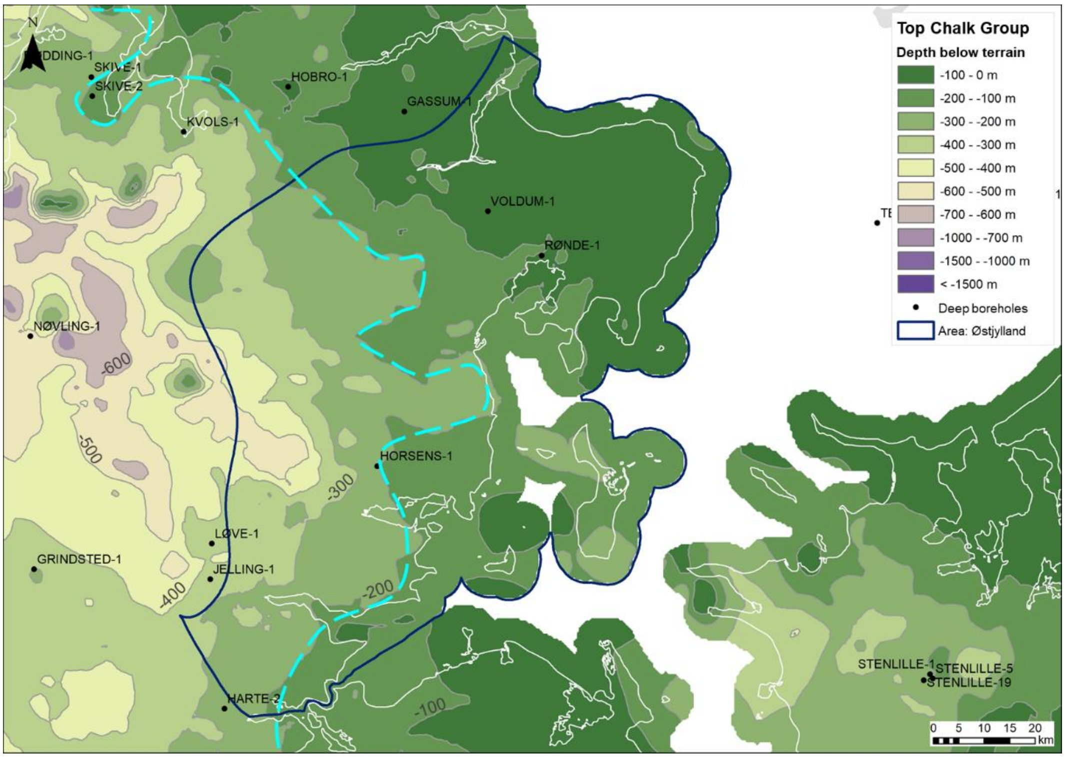


Figure 6.48. *Top Chalk Group depth map, Østjylland area. To the west of the dotted line, the top of the Chalk Group is deeper than 200 meters.*

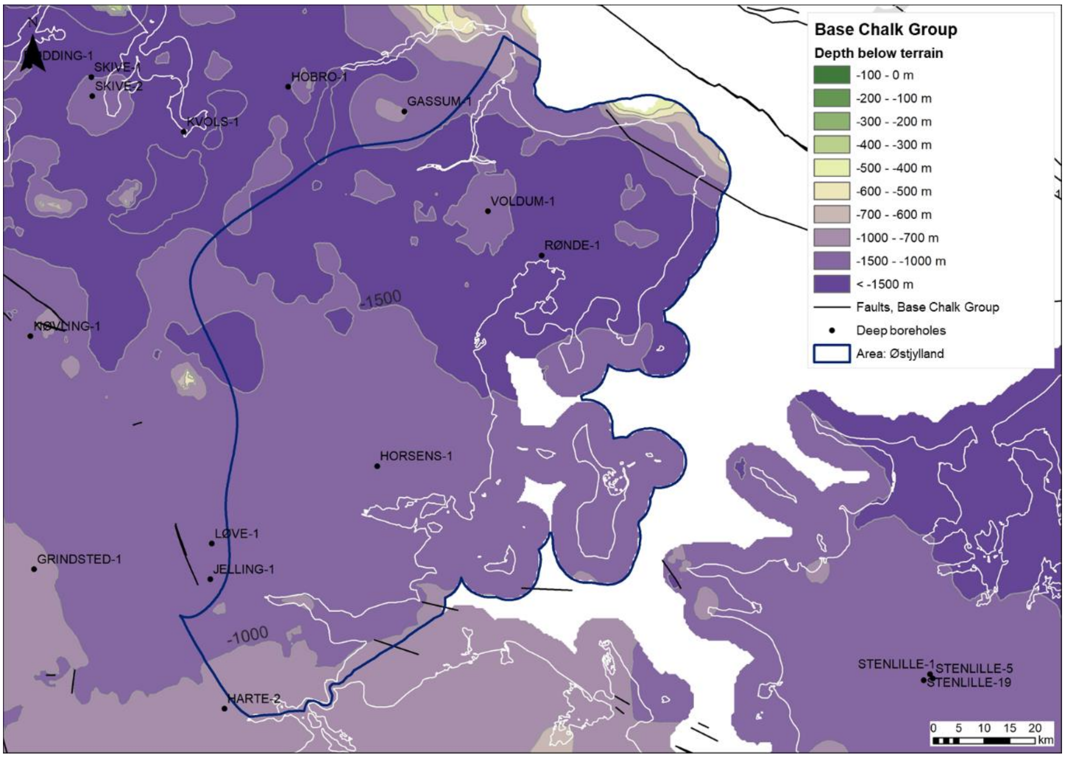


Figure 6.49. *Top Lower Cretaceous (base of the Chalk Group) depth map, Østjylland area. Mapped faults intersecting the base of the Chalk Group are shown. The map shows that the base of the Chalk Group occurs deeper than 1000 meters.*

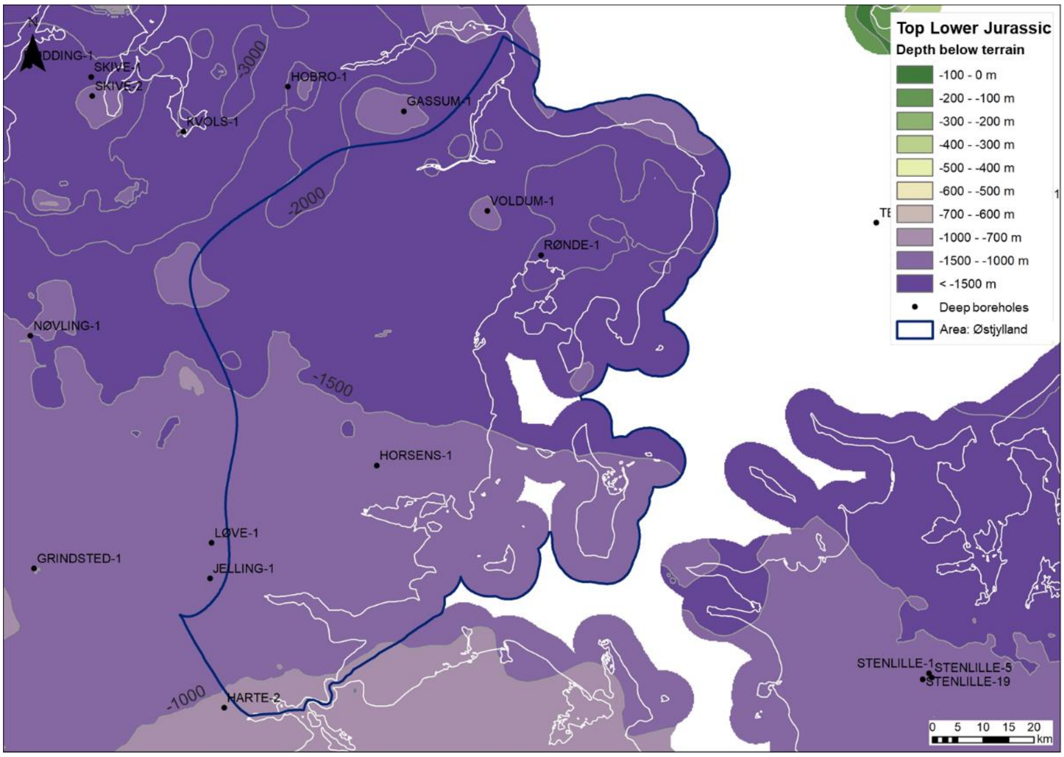


Figure 6.50. *Top Lower Jurassic depth map, Østjylland area.*

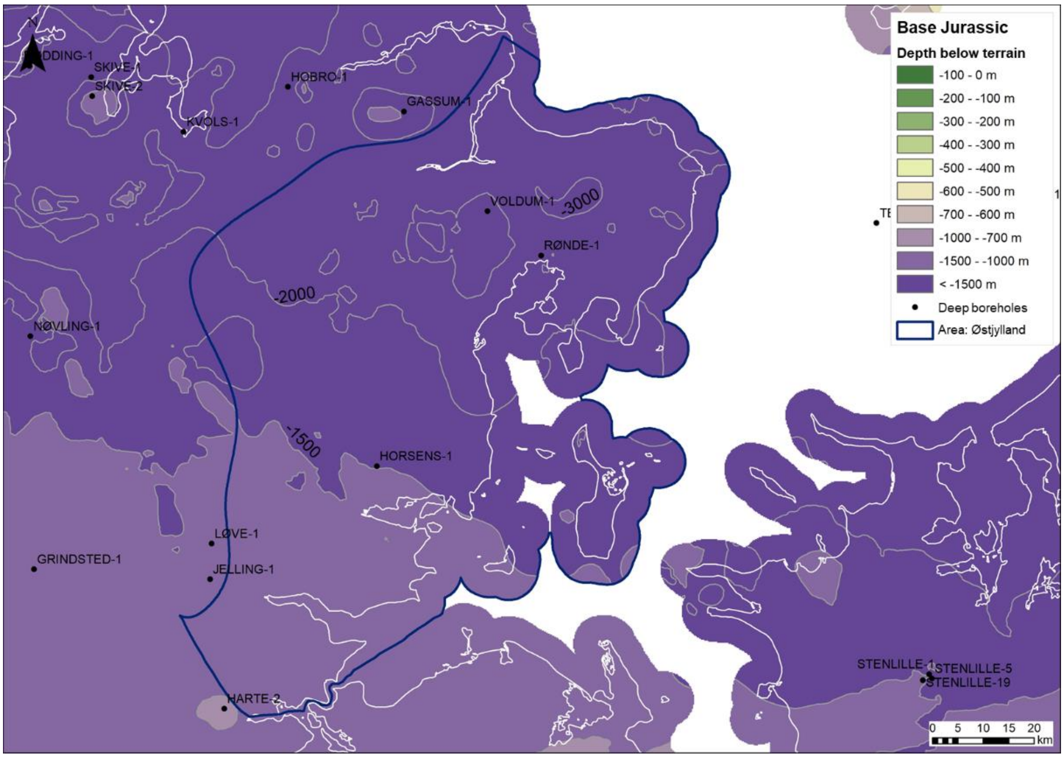


Figure 6.51. *Base Jurassic depth map, Østjylland area.*

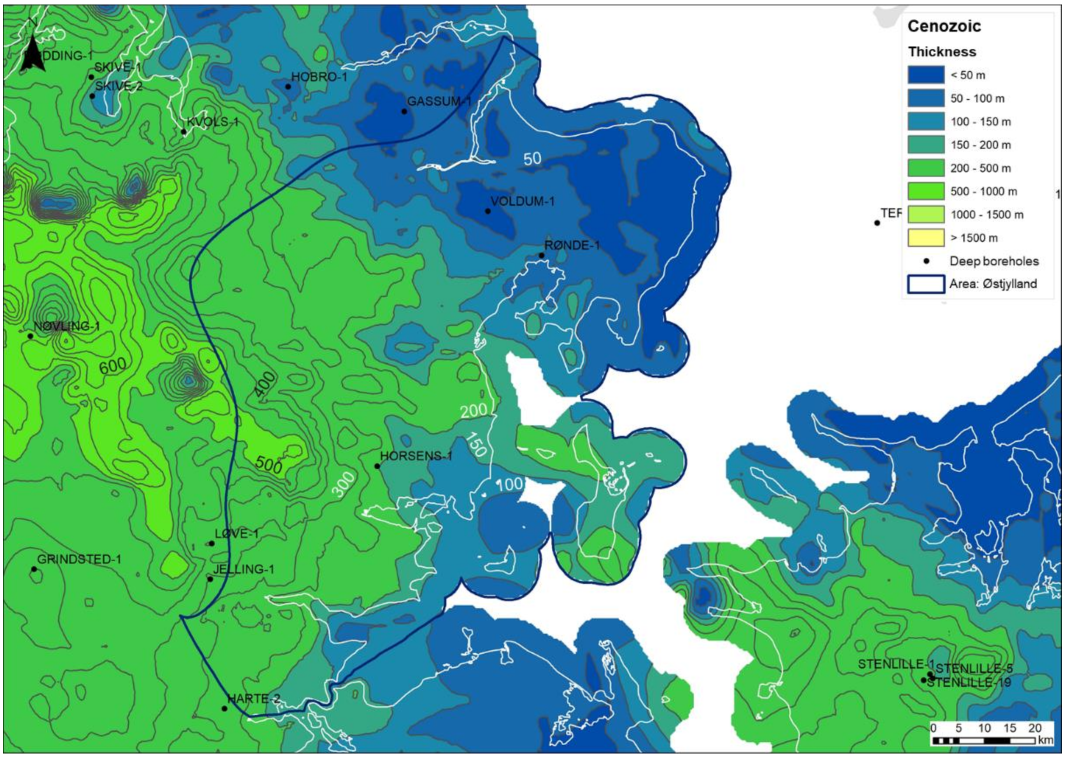


Figure 6.52. *Cenozoic thickness map, Østjylland area. The thickness increases towards the southwest and, locally, it exceeds 500 meters.*

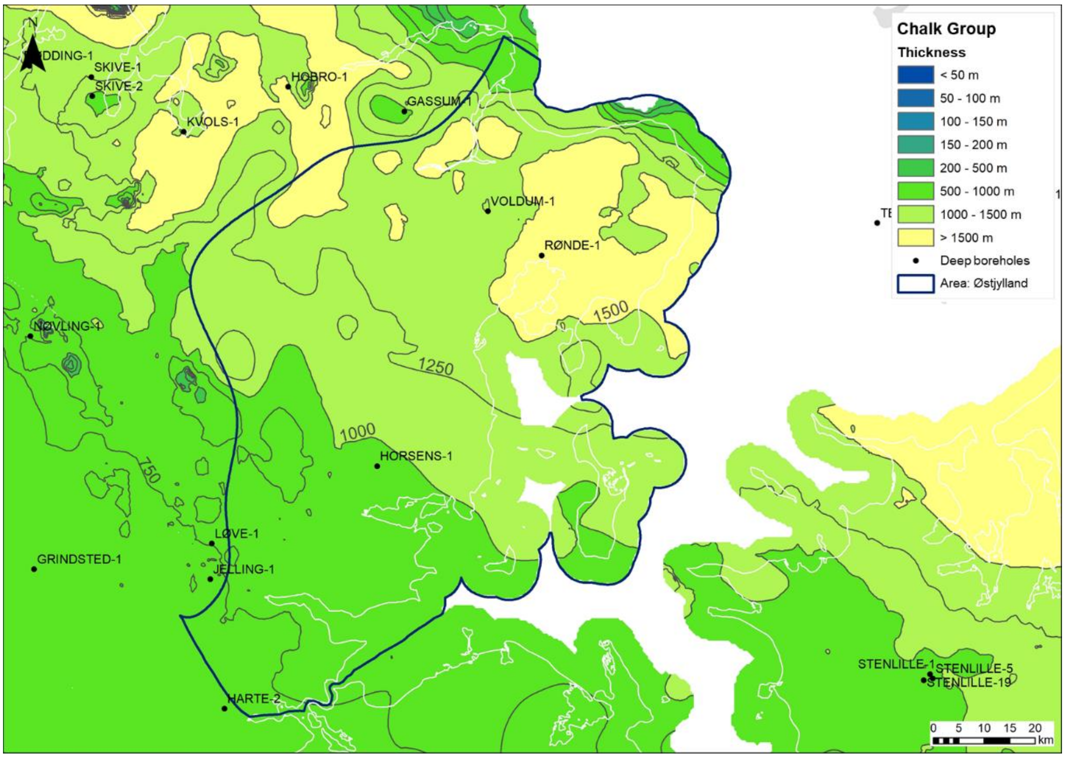


Figure 6.53. *Chalk Group thickness, Østjylland area. The map shows that the Chalk Group thickness increases from 750 meters in the south (green areas) to more than 1500 meters in the north (yellow areas).*

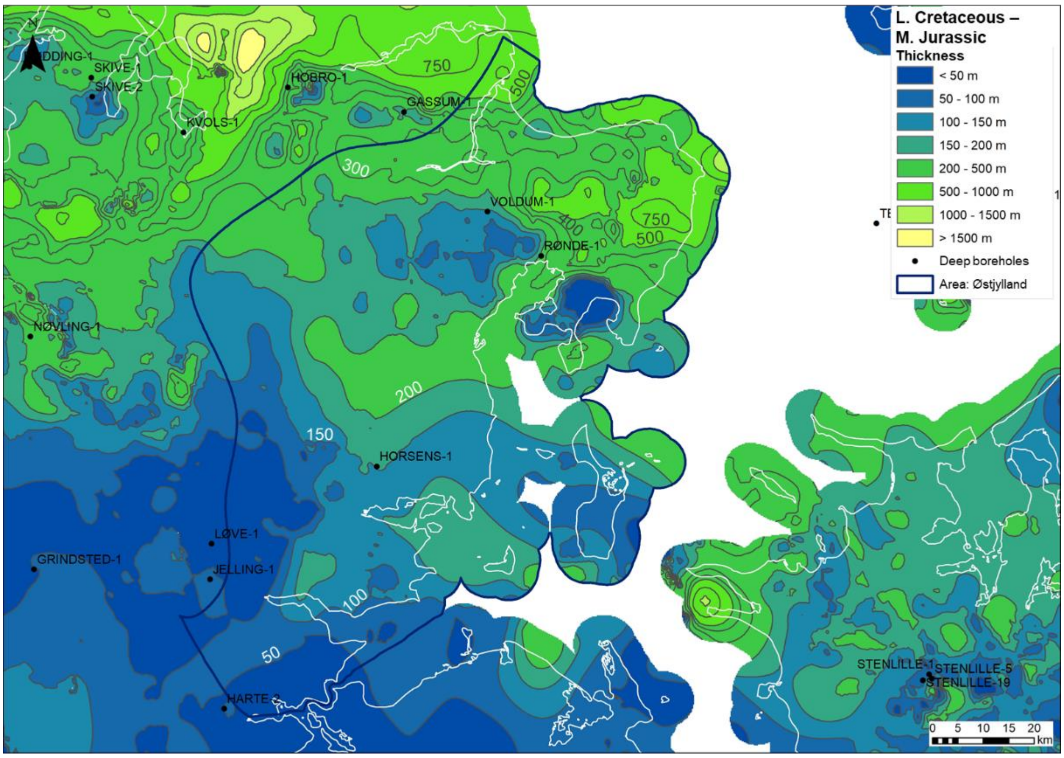


Figure 6.54. *Lower Cretaceous to Middle Jurassic thickness map, Østjylland area.*

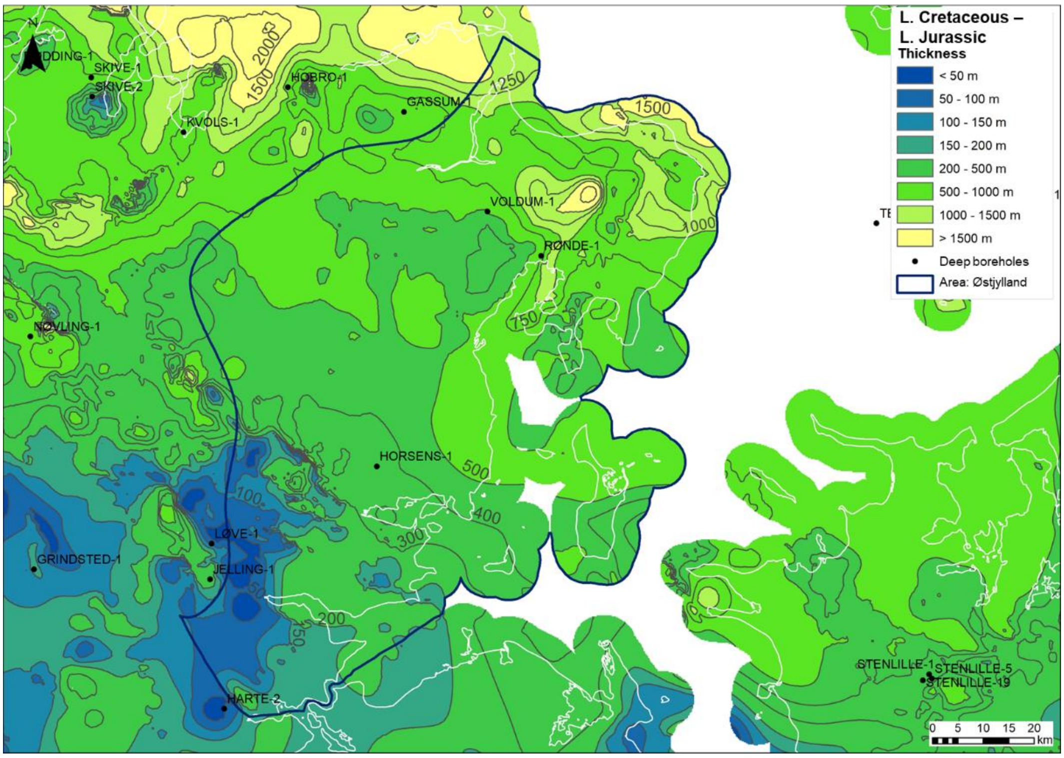


Figure 6.55. *Thickness map of the combined Lower Cretaceous and Jurassic sedimentary successions, Østjylland area.*

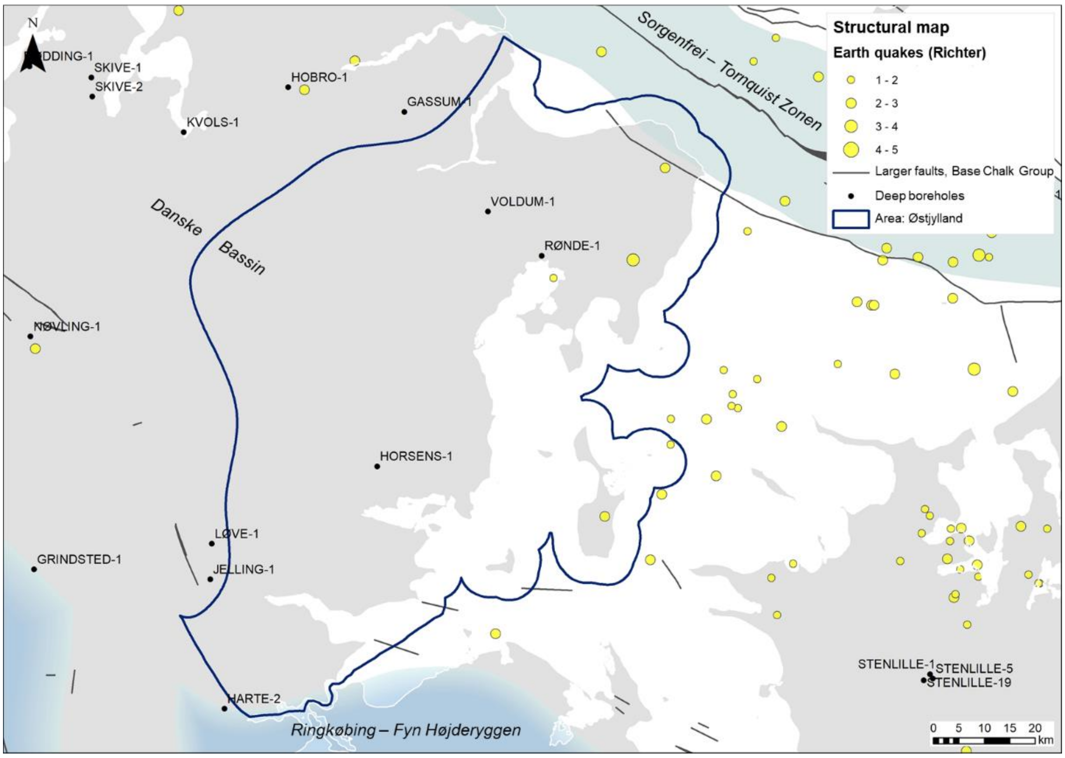
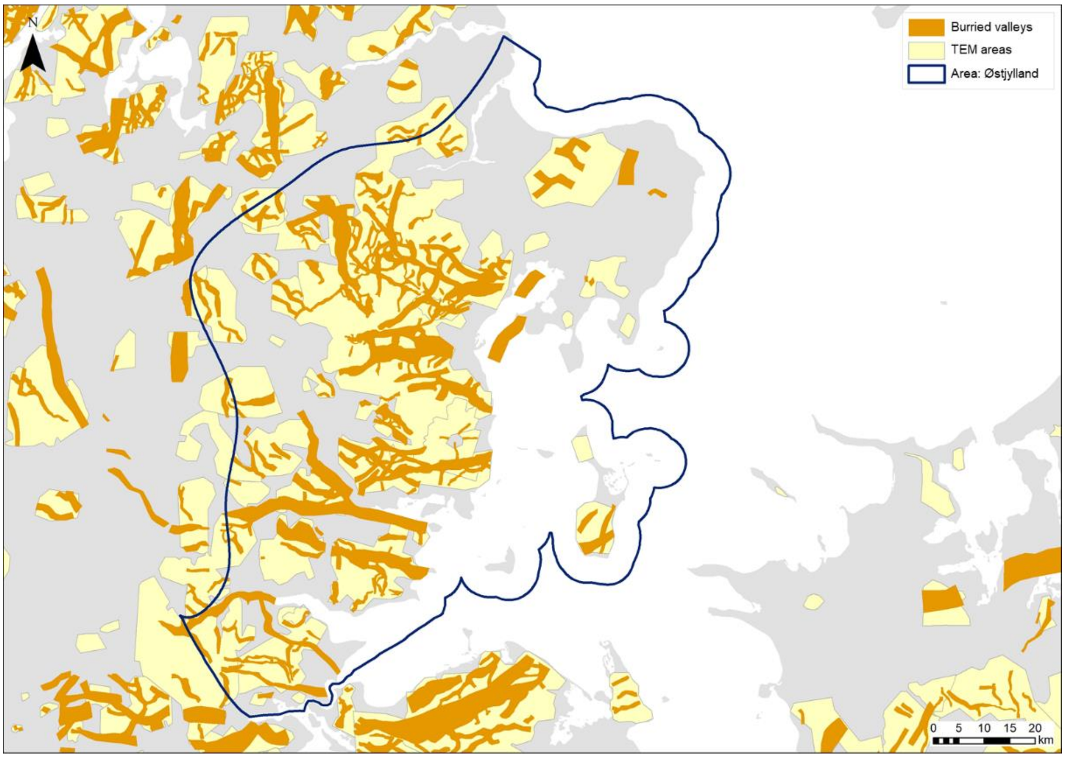


Figure 6.56. *Earthquakes registered during the past 50 years plotted on a structural map, Østjylland area. Only few earthquakes are registered in the area.*



*ey**Figure 6.57.** Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Østjylland area.*

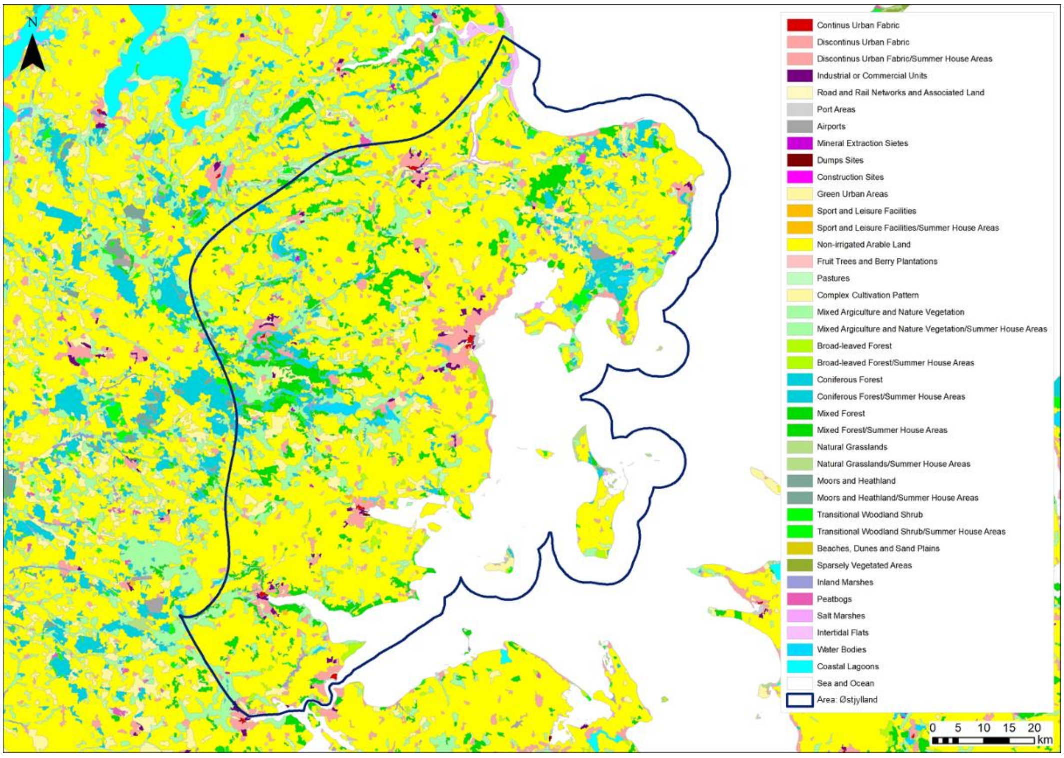


Figure 6.58. *Land use, Østjylland area (MiljøGIS, 2021).*

6.5 Sydvestjylland

Carbonate is the host rock in the Sydvestjylland area, as the 400–500 meters depth interval in the entire area comprises carbonates from the Chalk Group. The carbonates continue downwards to depths of around 1000 meters or more (Figures 4.15, 4.18, and 6.63). Top Chalk Group occurs at approximately 400 meters depth (Figure 6.62) and is overlain by Cenozoic sediments (Figure 6.61). In the ECZ a maximum of 100 meters of carbonate is present above 500 meters depth, and the thickness requirement for tight rocks in the barrier zone is not fulfilled. Therefore, the criterion 1.1 has an orange score (less suitable).

As the carbonate thickness is 500–1000 meters (Figure 6.67), a sufficiently thick barrier of carbonate can be achieved if a repository is established deeper than 500 meters.

Table 6.7. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Sydvestjylland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

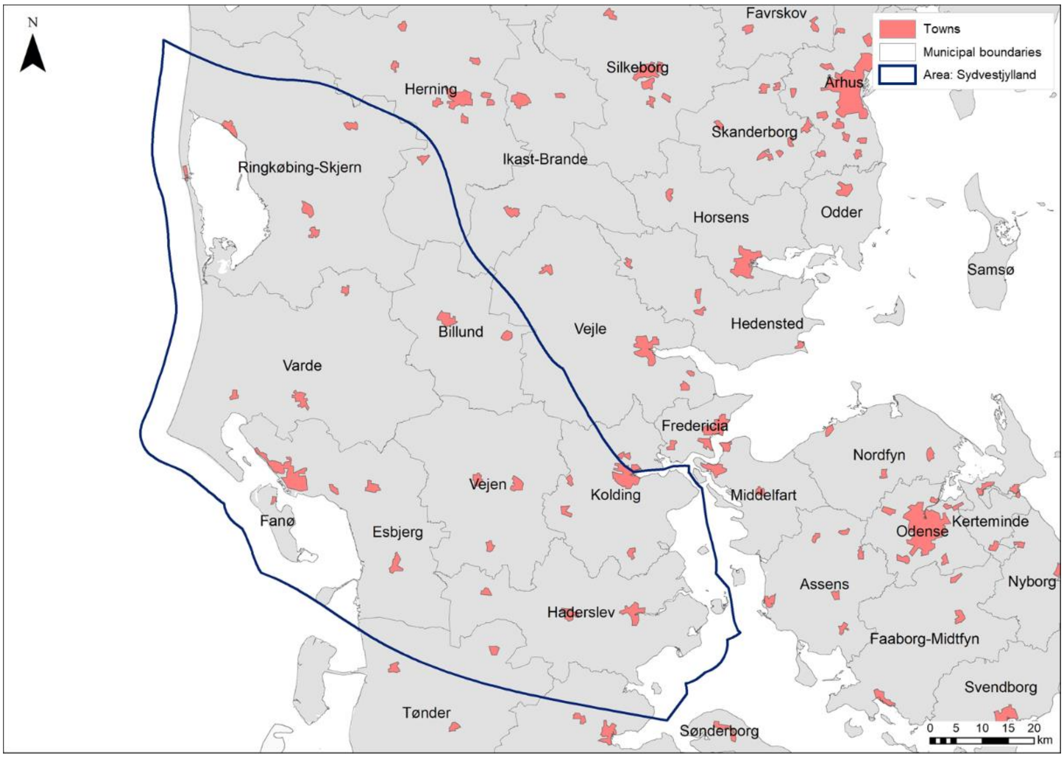


Figure 6.59. *Geographic outline of the Sydvestjylland area with towns and municipal boundaries indicated.*

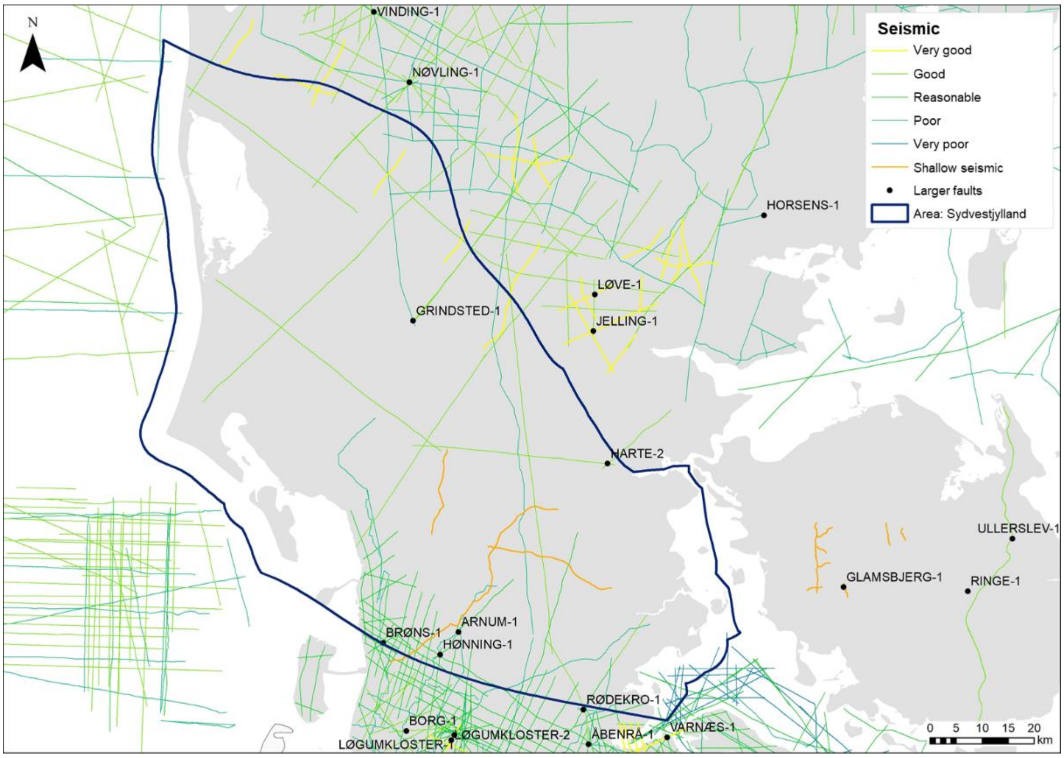


Figure 6.60. *Location map showing seismic lines and their quality, and deep boreholes in the Sydvestjylland area. The map shows that seismic data coverage is sparse in the central part of the area.*

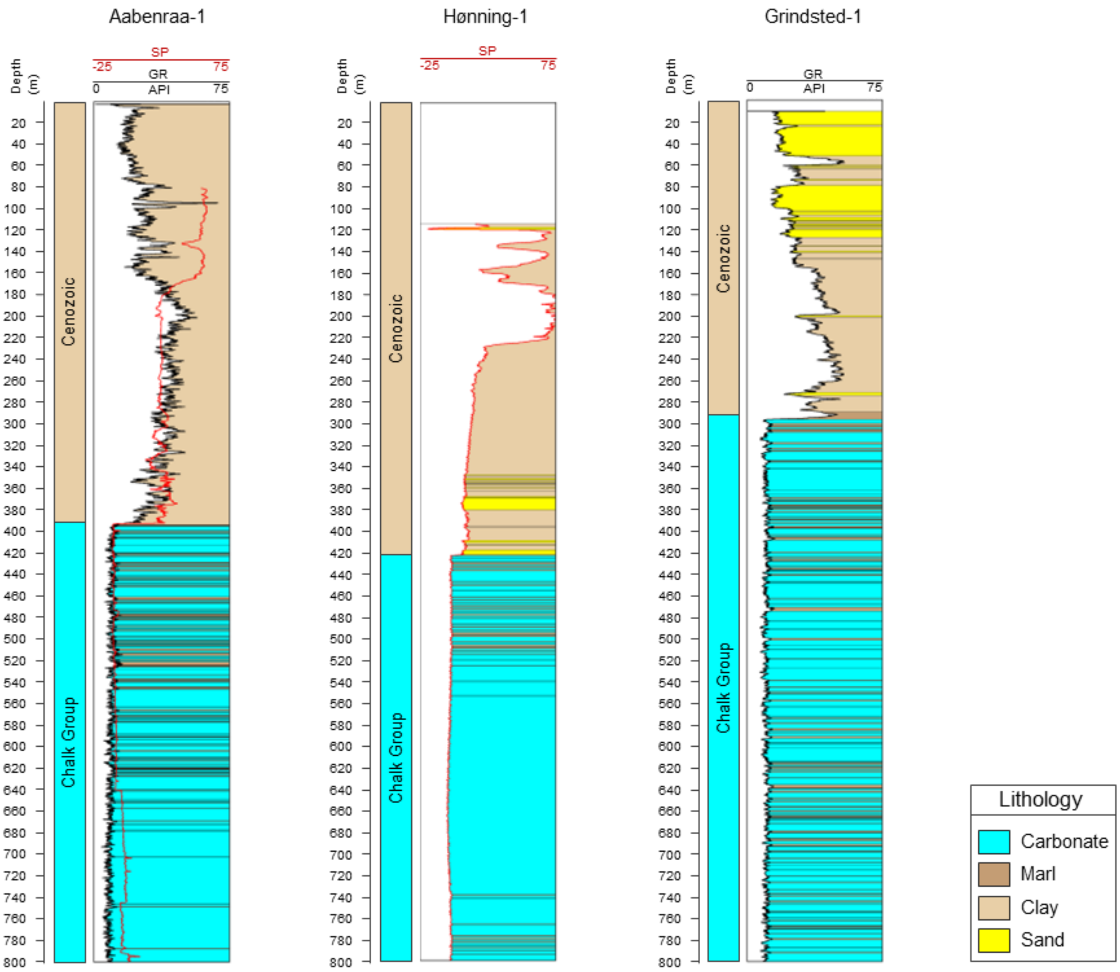


Figure 6.61. *Lithological log interpretations of the 0–800 meters depth interval representative of the Sydvestjylland area show that carbonates occur from 300–400 meters depth to more than 800 meters. Clay-rich intervals (marl) are common in the carbonate successions. The overlying Cenozoic succession consists of alternating clay and sand layers.*

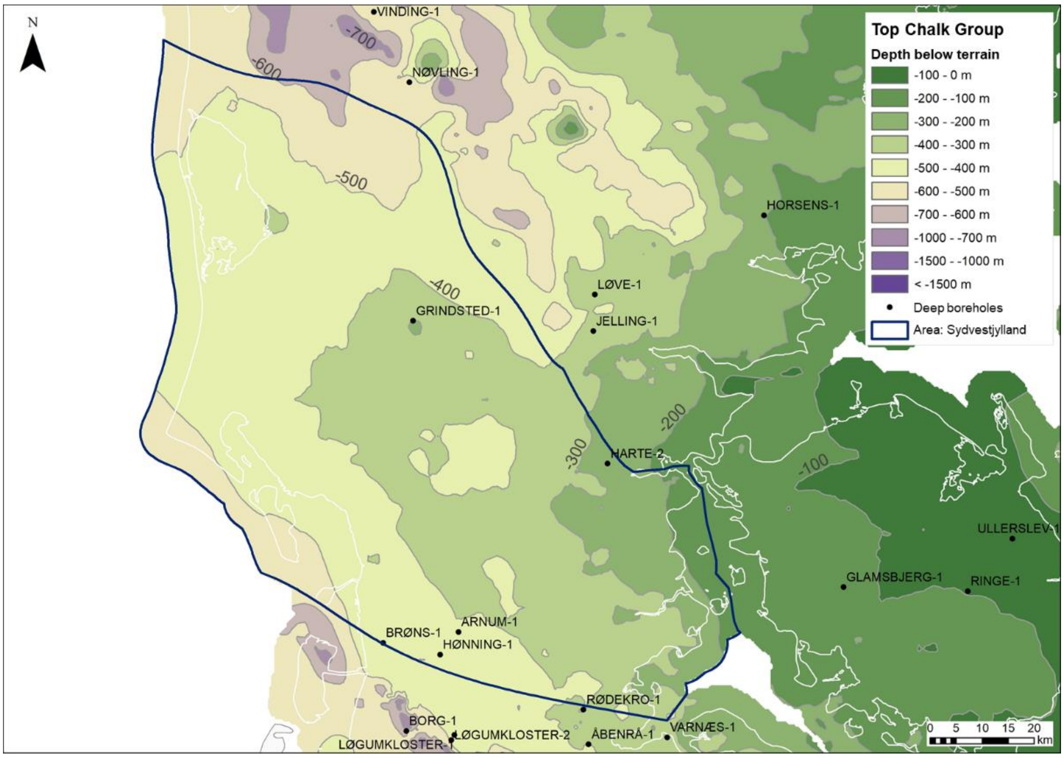


Figure 6.62. *Top Chalk Group depth map, Sydvestjylland area. The depth increases from 300 meters in the east (green) to more than 500 meters towards the northwest.*

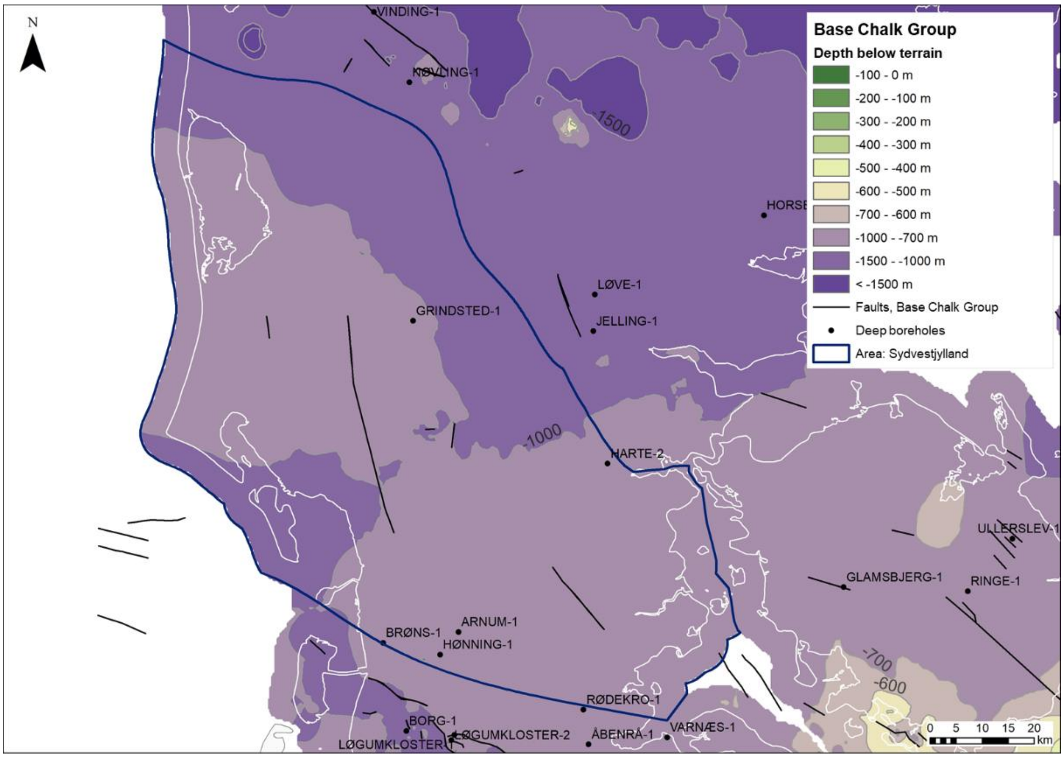


Figure 6.63. *Top Lower Cretaceous (base of the Chalk Group) depth map, Sydvestjylland area. Mapped major faults intersecting the base of the Chalk Group are shown. The map shows that the base of the Chalk Group occurs at depths from 600 meters (light purple) to more than 1000 meters in the north (purple).*

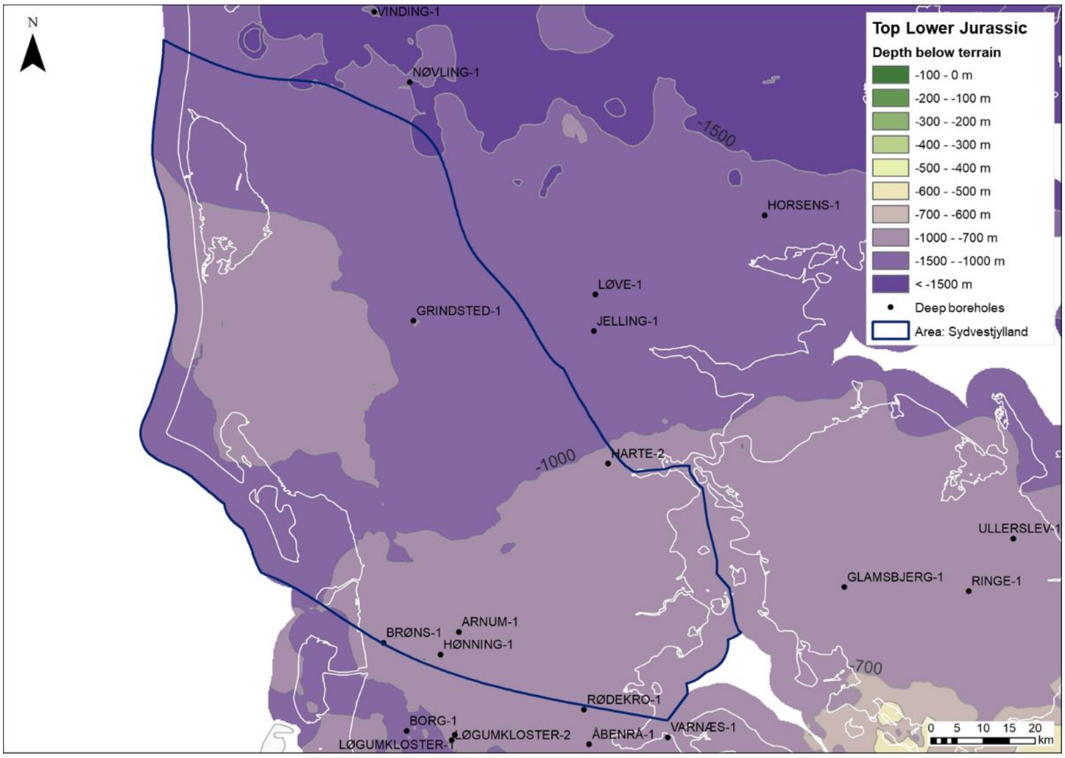


Figure 6.64. *Top Lower Jurassic depth map, Sydvestjylland area.*

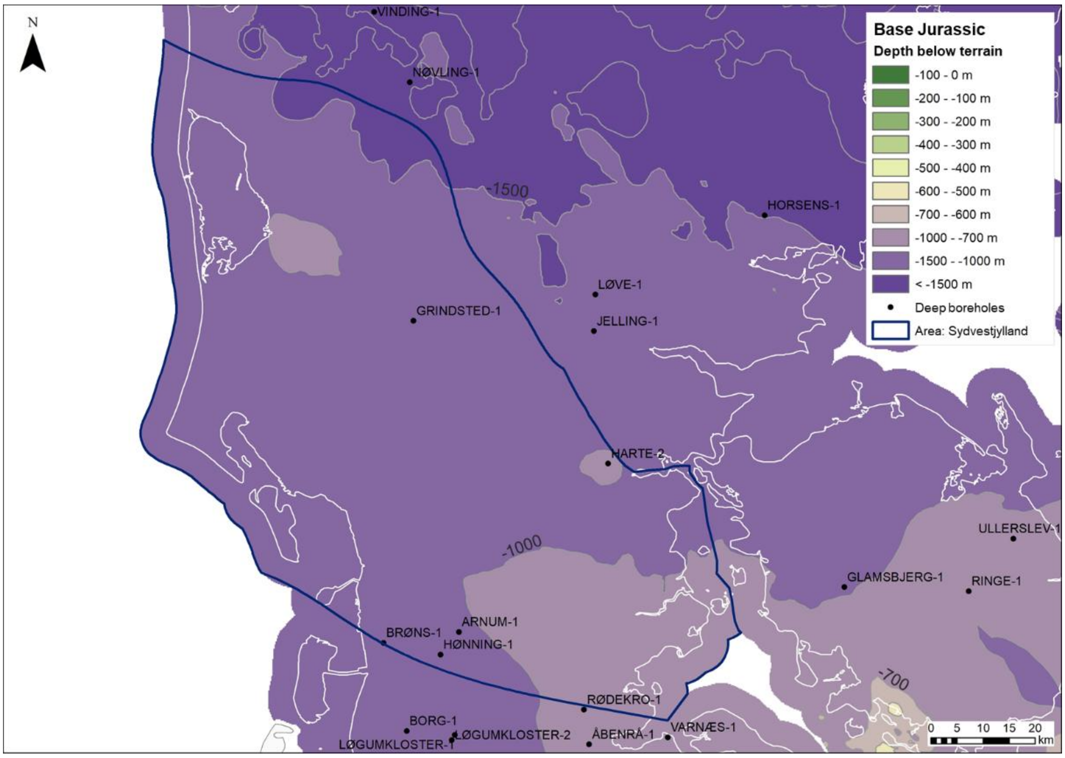


Figure 6.65. *Base Jurassic depth map, Sydvestjylland area.*

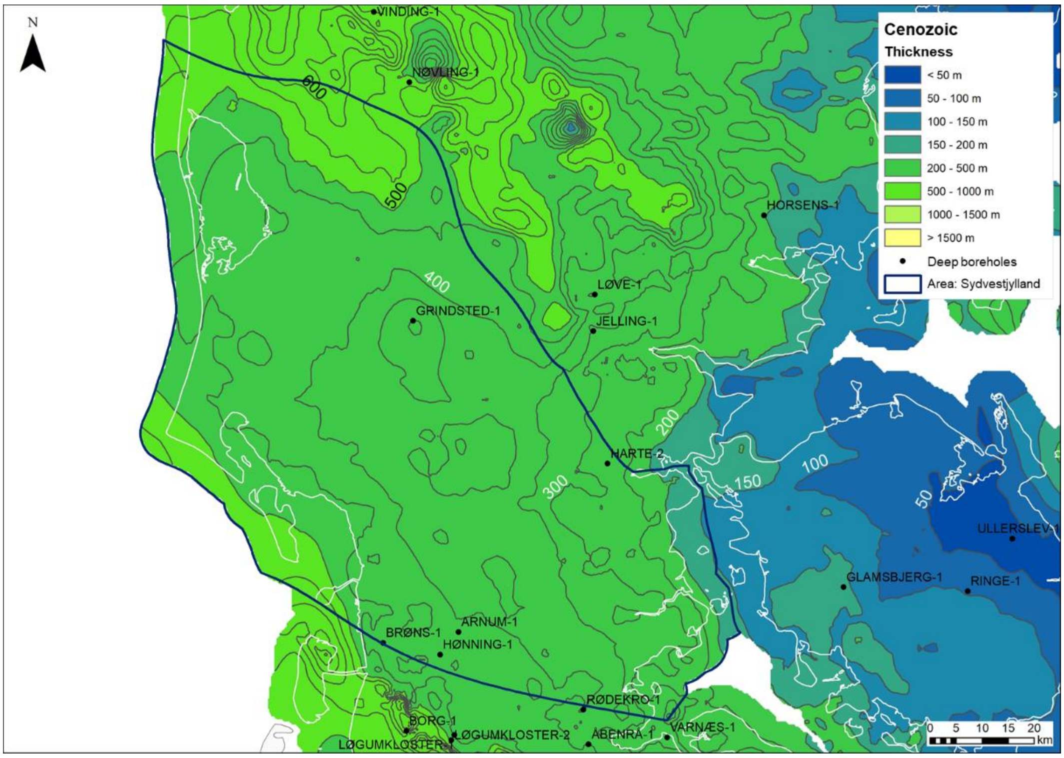


Figure 6.66. *Thickness map of the Cenozoic sedimentary succession, Sydvestjylland area. The map illustrates that the thickness increases from around 300 meters in the east to more than 500 meters in the northeast.*

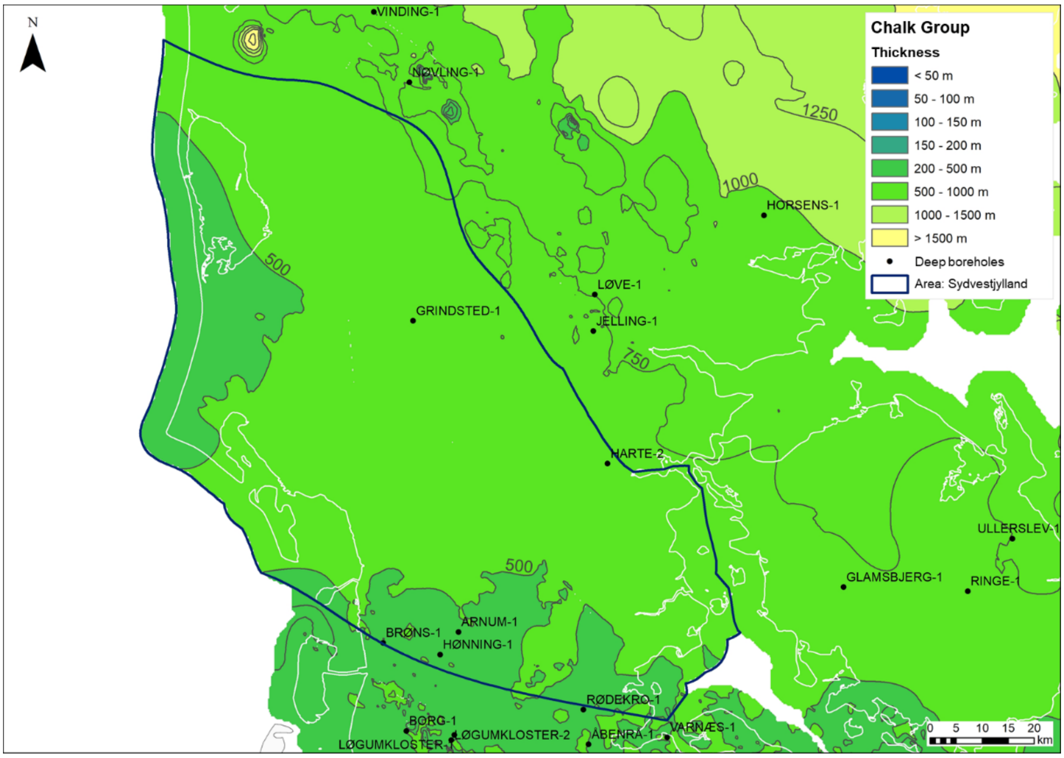


Figure 6.67. *Thickness map of the Chalk Group, Sydvestjylland area. The map shows that the Chalk Group thickness exceeds 500 meters in most of the area.*

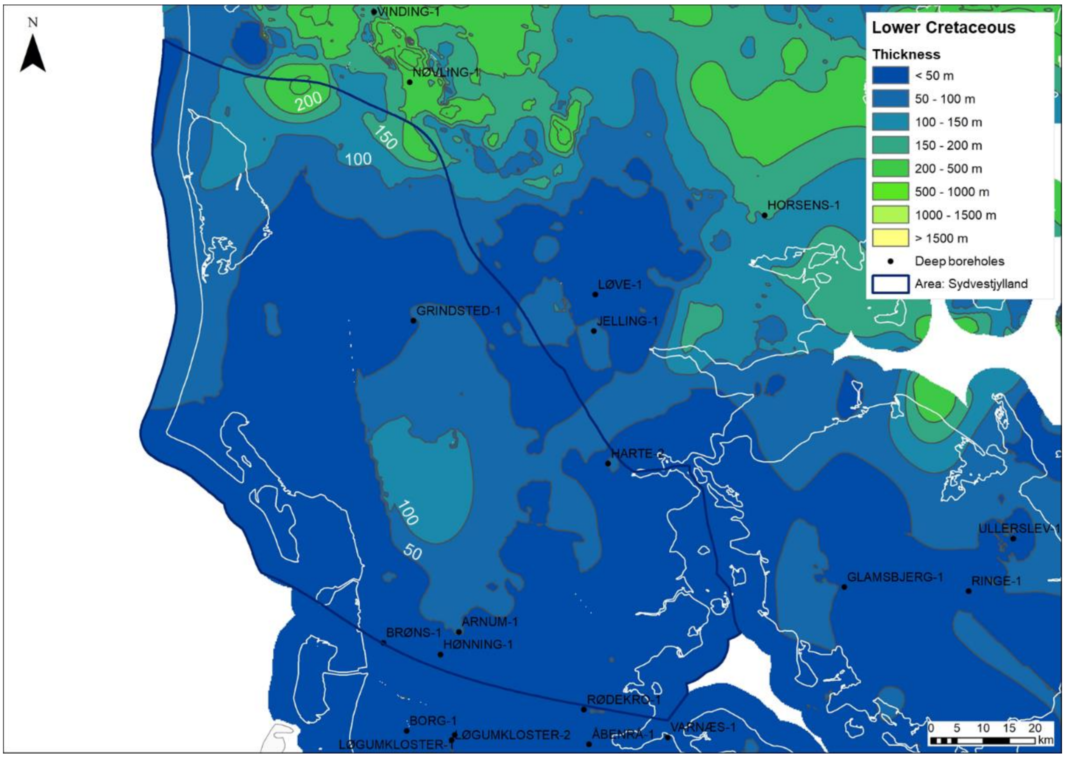


Figure 6.68. *Thickness map of the Lower Cretaceous succession, Sydvestjylland area. The thickness varies between 0 and 150 meters.*

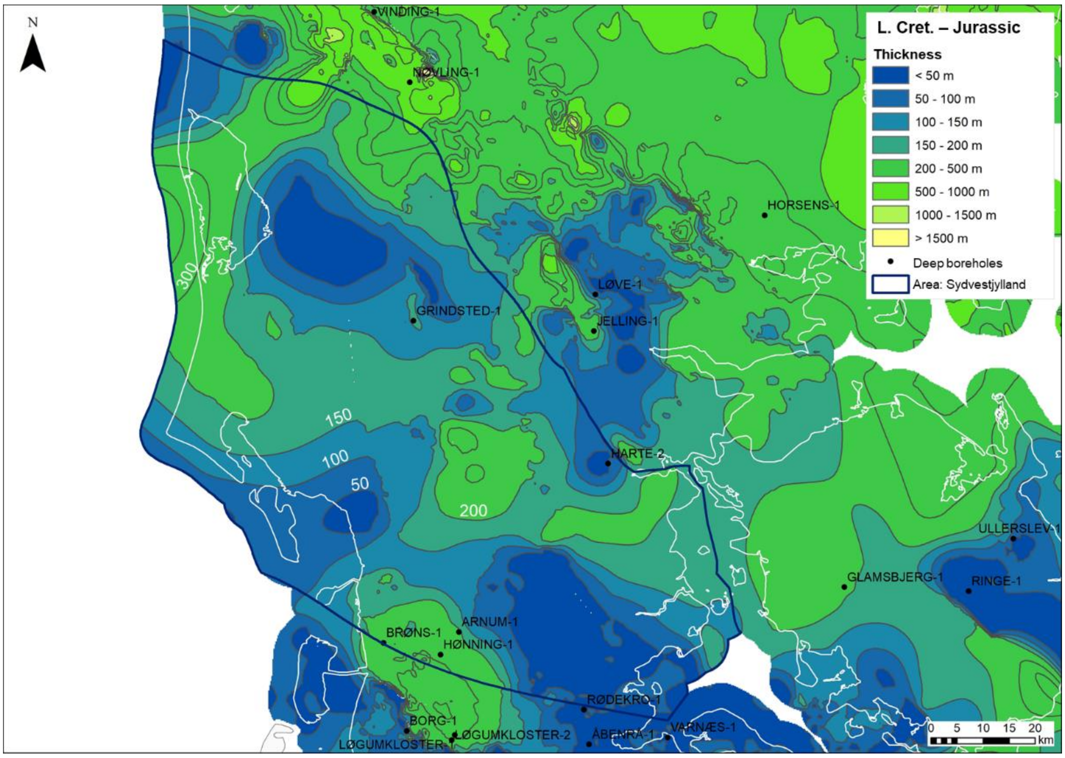


Figure 6.69. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Sydvestjylland area. The map illustrates that the thickness generally varies between 0 and 200 meters.*

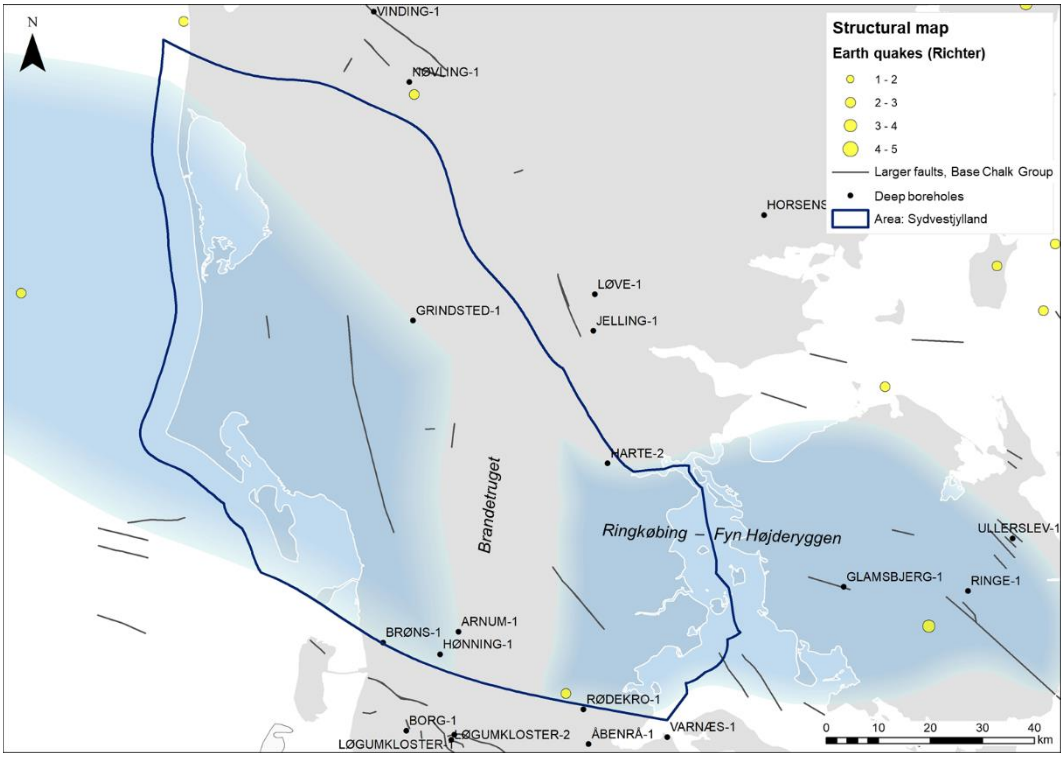


Figure 6.70. *Earthquakes registered during the past 50 years plotted on a structural map, Sydvestjylland area. Very few and small earthquakes are registered in and adjacent to the area.*

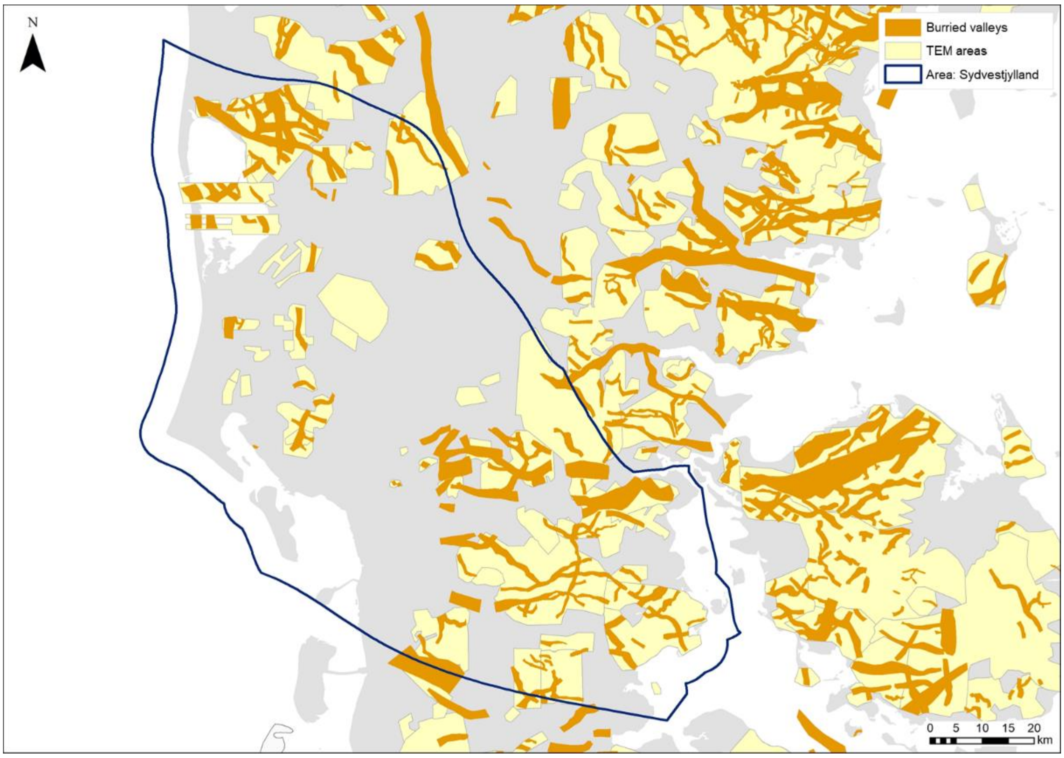


Figure 6.71. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Sydvestjylland area.*

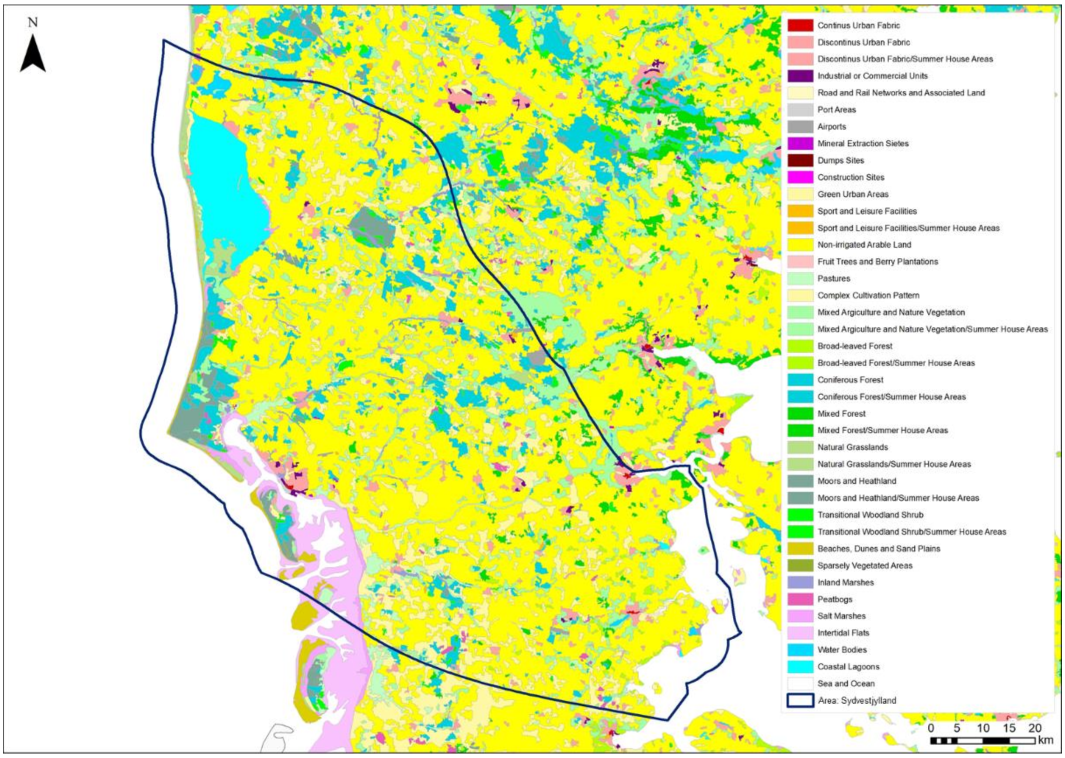


Figure 6.72. *Land use, Sydvestjylland area. Extensive lagoons and marsh areas exist along the west coast (light blue and pinkish areas) (MiljøGIS, 2021).*

6.6 Sønderjylland

Carbonate provides a potential host rock in the Sønderjylland area as the Chalk Group constitutes the 400–500 meters depth interval in large parts of the area. However, in a 10 kilometer wide WN–-ESE striking zone across the area, the top of the Chalk Group occurs at depths exceeding 500 meters (Figures 4.19, 6.75 and 6.76). In most of the area the carbonate succession is less than 100 meters thick in the ECZ and locally 200 meters in the easternmost part of the area. Thus, the criterion on 250 meters of tight rock in the ECZ (criterion 1.1) is not met in the area. The base of the Chalk Group occurs at 700 meters or deeper (Figure 6.77).

The horizontal continuity of the carbonate section is generally less suitable, as numerous deep faults are mapped as continuing into the Chalk Group carbonates and some continue further into the Cenozoic section (Figures 4.18 and 4.19). The general lack of horizontal continuity of the potential host rock is an additional less favourable condition for the spatial extent which contributes to the orange score of criterion no.1.1.

Table 6.8. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Sønderjylland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

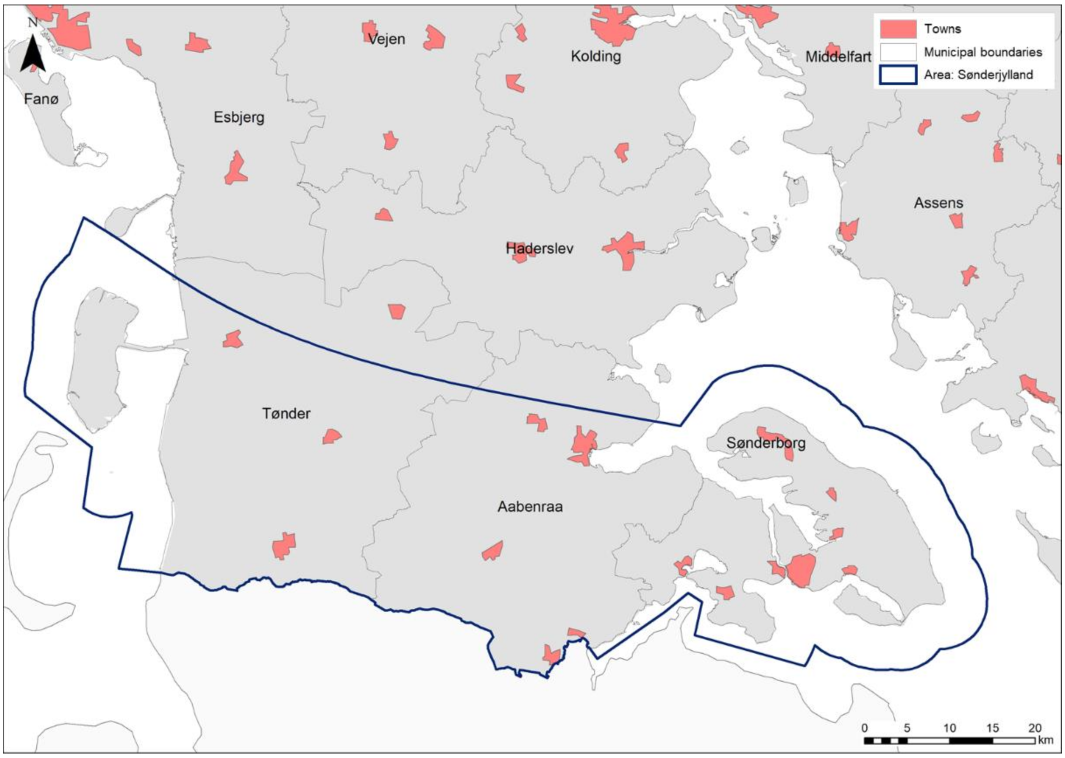


Figure 6.73. *Geographic outline of the Sønderjylland area with towns and municipal boundaries indicated.*

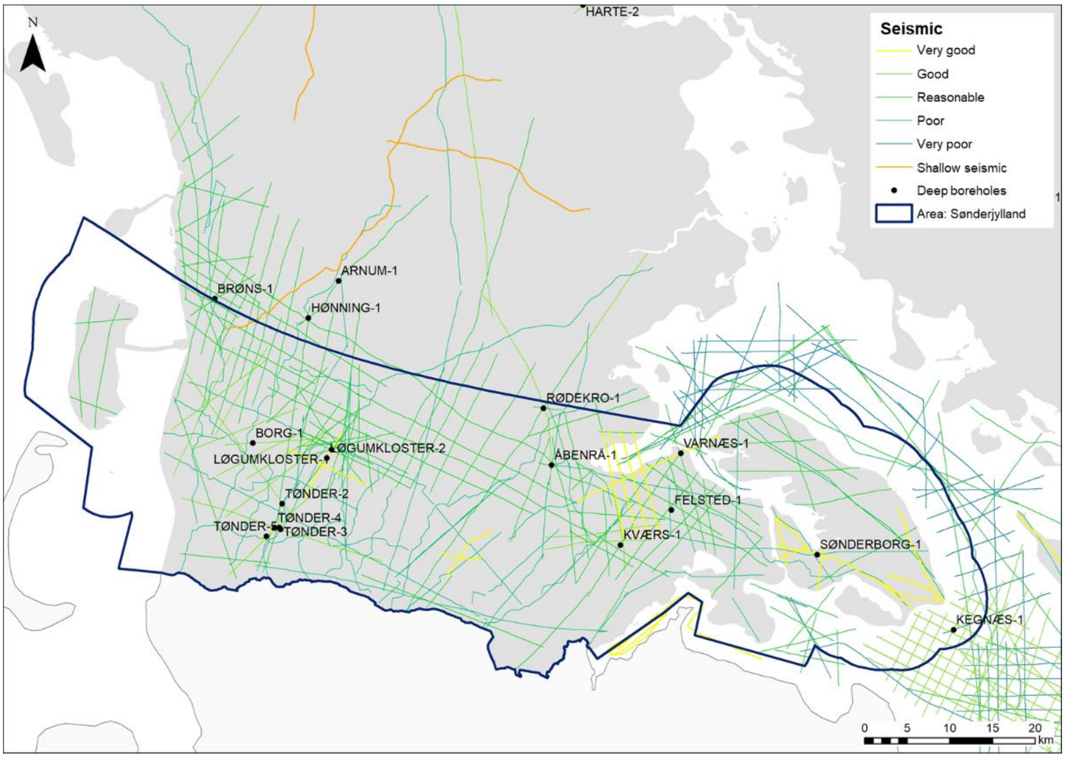


Figure 6.74. *Location map showing seismic lines and their quality, and deep boreholes in the Sønderjylland area. In this area, the seismic data coverage is relatively good.*

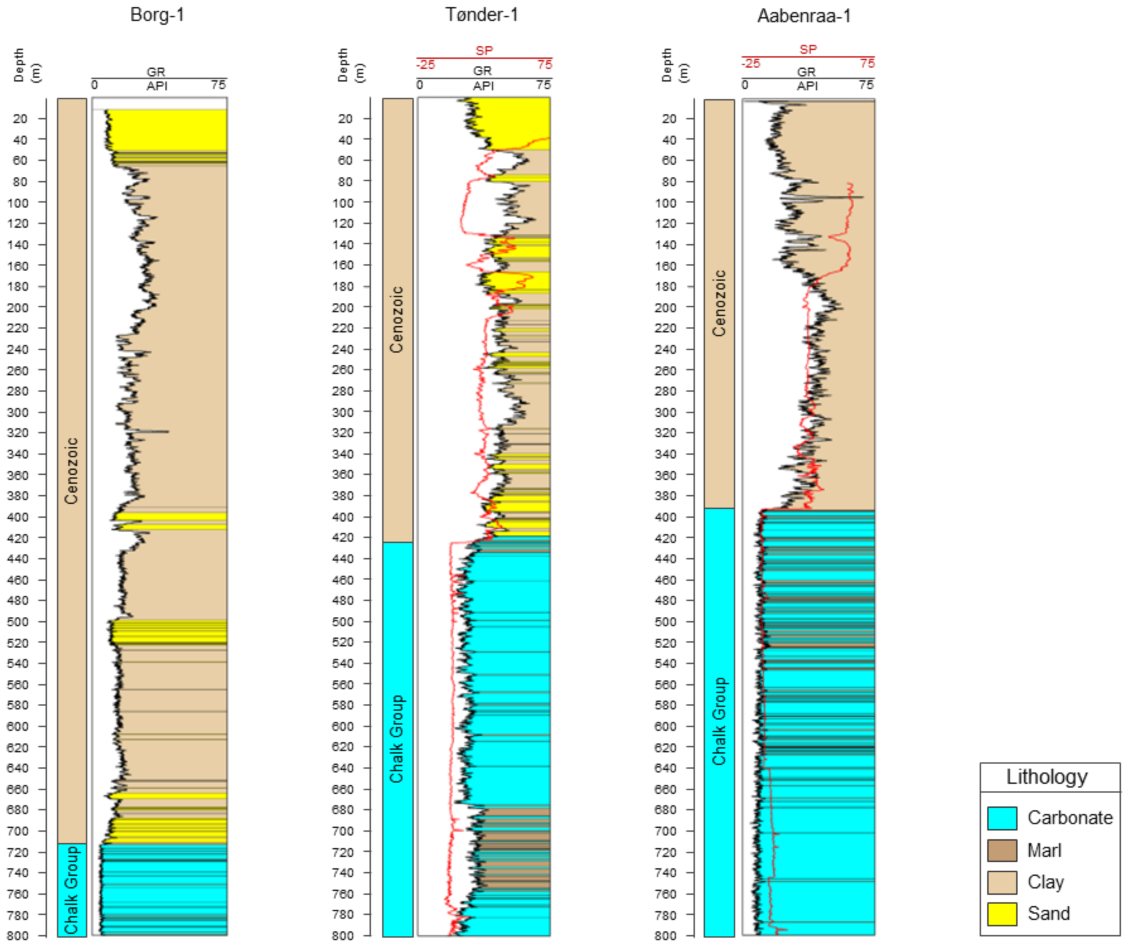


Figure 6.75. *Lithological log interpretations of the 0–800 meters depth interval of deep bore-holes in the Sønderjylland area. The logs show that the top of the Chalk Group occurs at depths varying from 400 meters (Aabenrå-1) to more than 700 meters (Borg-1). The car-bonates are overlain by Cenozoic sediments of alternating clay and sand layers which are not regarded as potential barriers.*

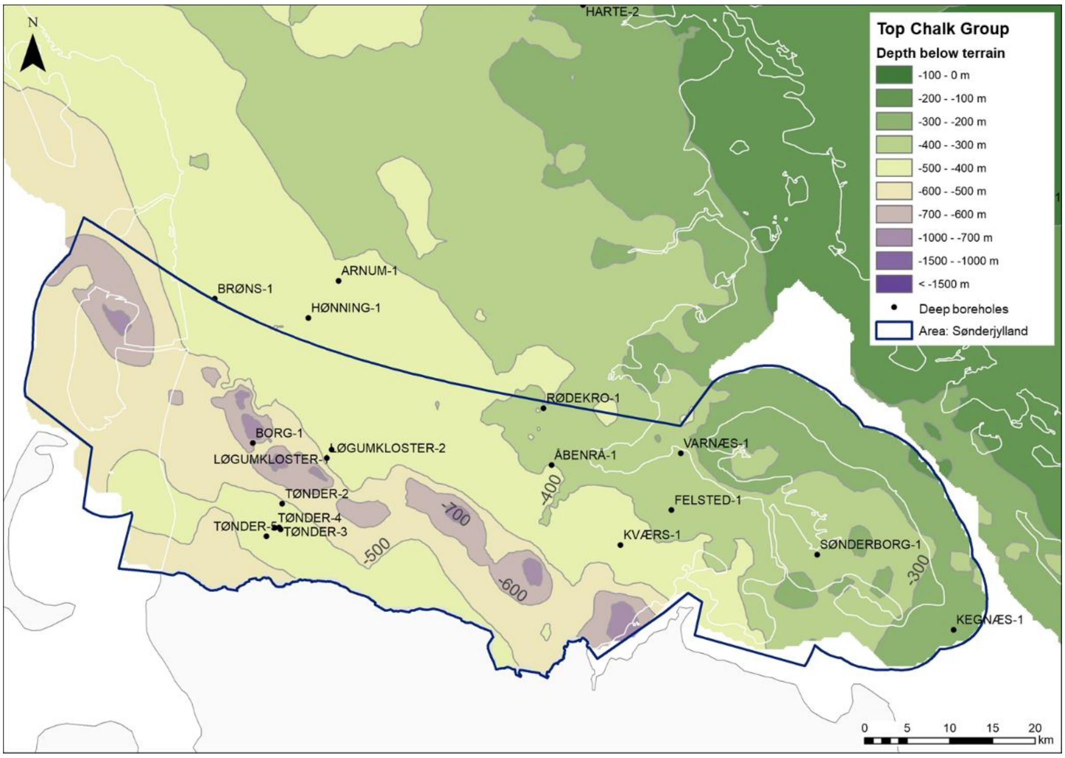


Figure 6.76. *Top Chalk Group depth map, Sønderjylland area, showing the depths ranging from 300 to more than 700 meters. In the purple and yellow areas, the depth exceeds 500 meters, and the deeper burial is mainly a result of remobilization of underlying salt (see also Figure 4.19).*

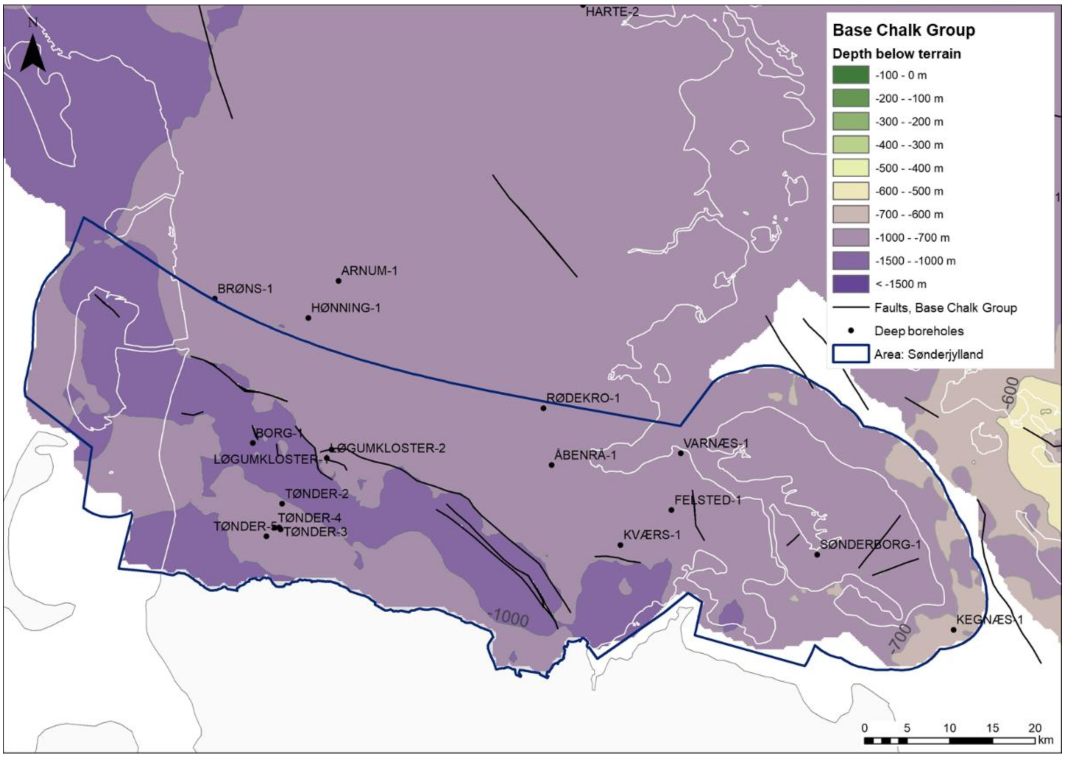


Figure 6.77. *Top Lower Cretaceous (Base Chalk Group) depth map, Sønderjylland area. Mapped faults intersecting the base of the Chalk Group are shown. The map shows that the base of the Chalk Group occurs at depths exceeding 700 meters.*

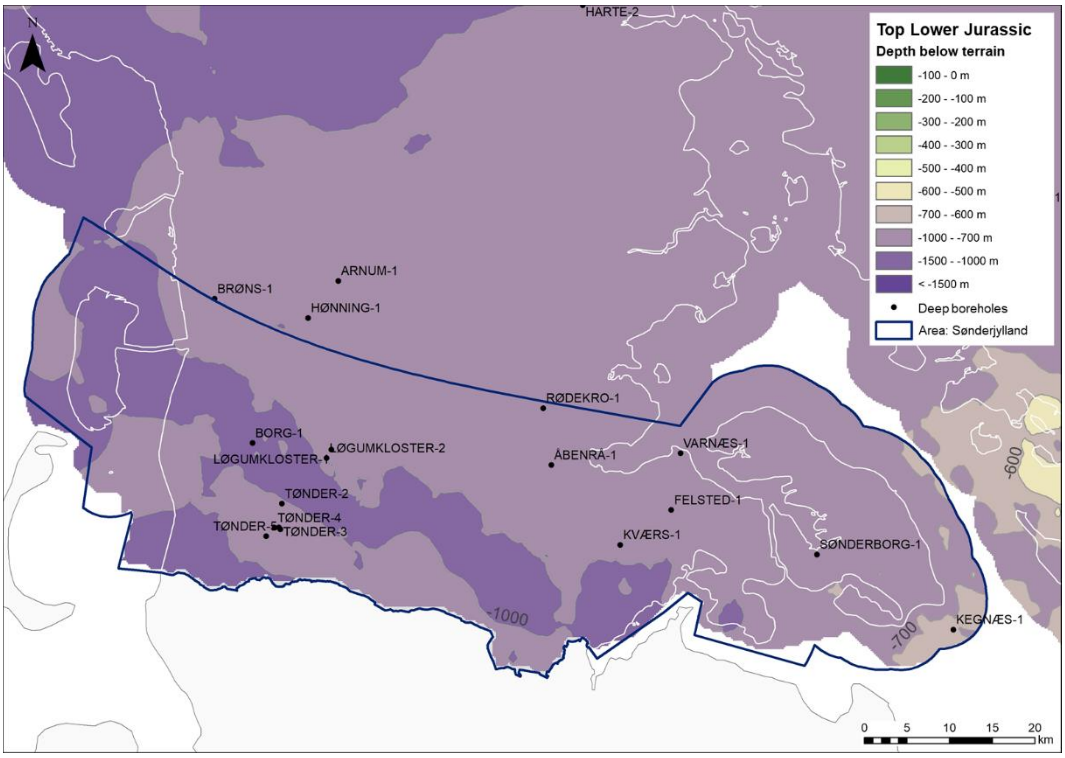


Figure 6.78. *Top Lower Jurassic depth map, Sønderjylland area.*

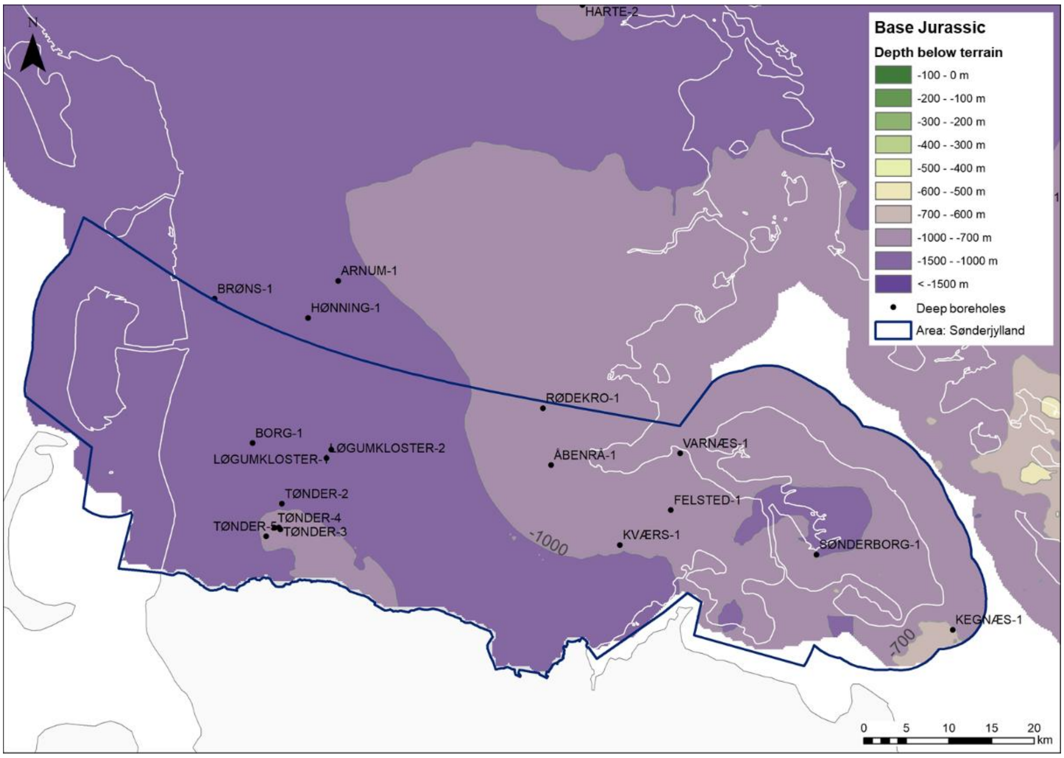


Figure 6.79. *Base Jurassic depth map, Sønderjylland area.*

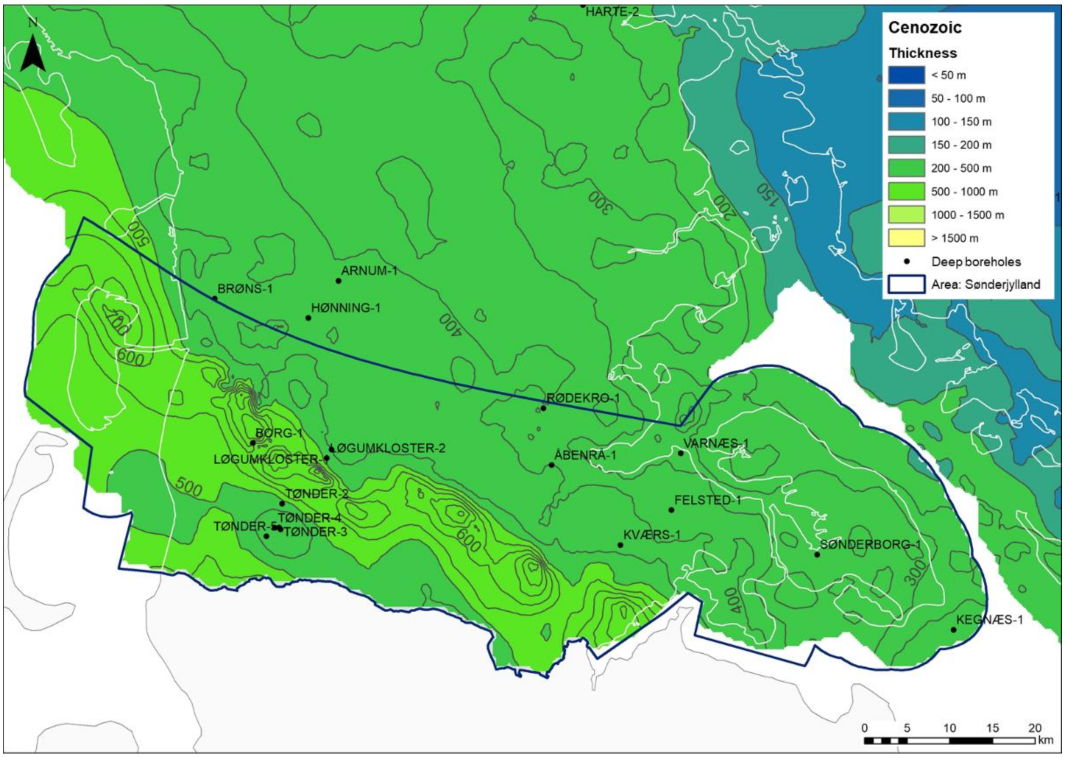


__Figure 6.80.__ Cenozoic thickness map, Sønderjylland. The map illustrates that the thickness of the Cenozoic succession exceeds 400 meters in most of the area.

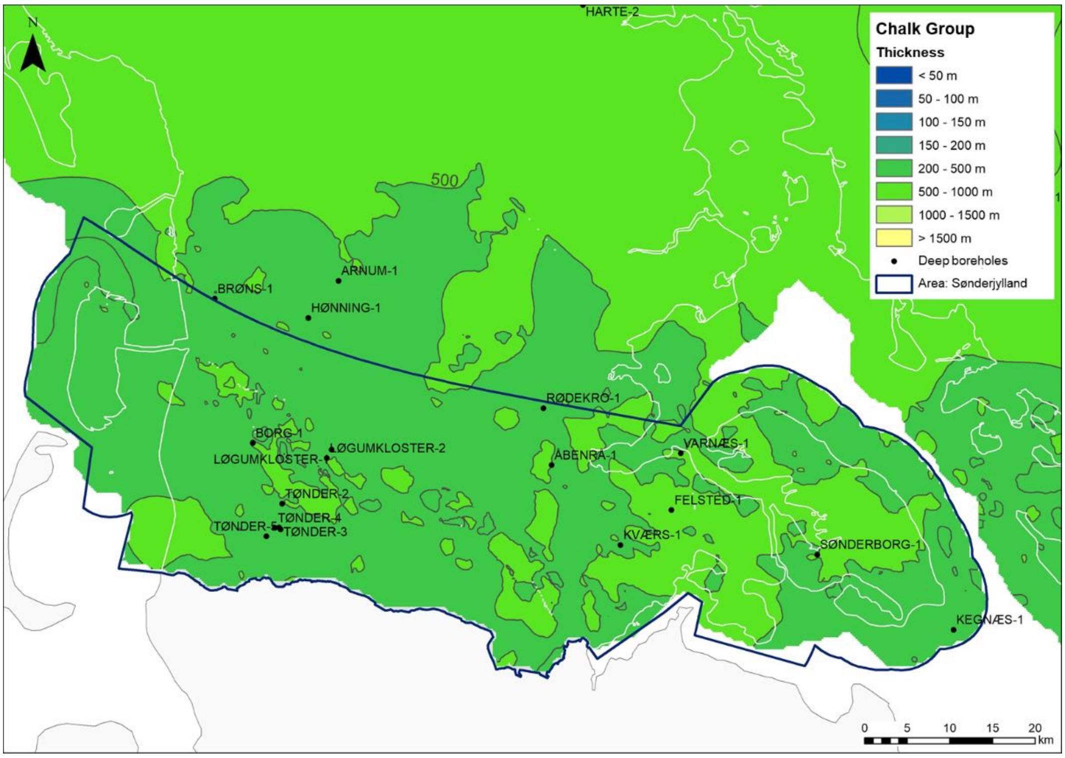


__Figure 6.81.__ Chalk Group thickness map, Sønderjylland area. The map shows, that the thickness generally is in the ranges from 200 and 500 meters.

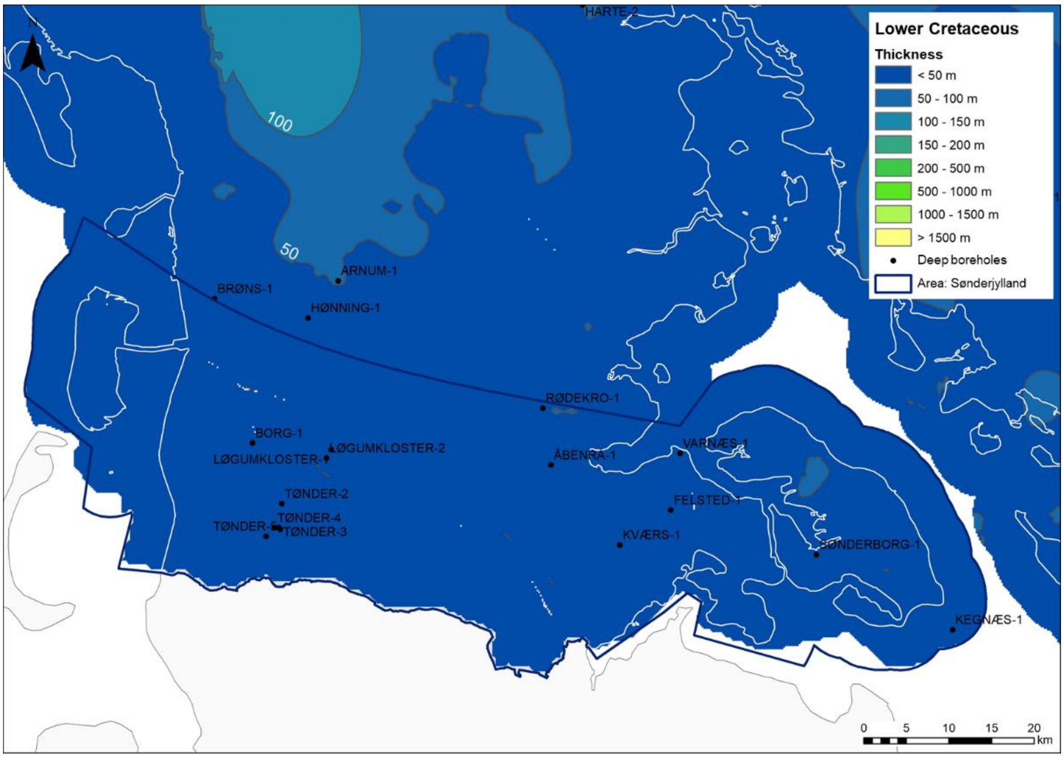


Figure 6.82. *Lower Cretaceous thickness map, Sønderjylland area. The map shows the thickness is less than 50 meters and well data shows that the Lower Cretaceous interval is absent in large parts of the area.*

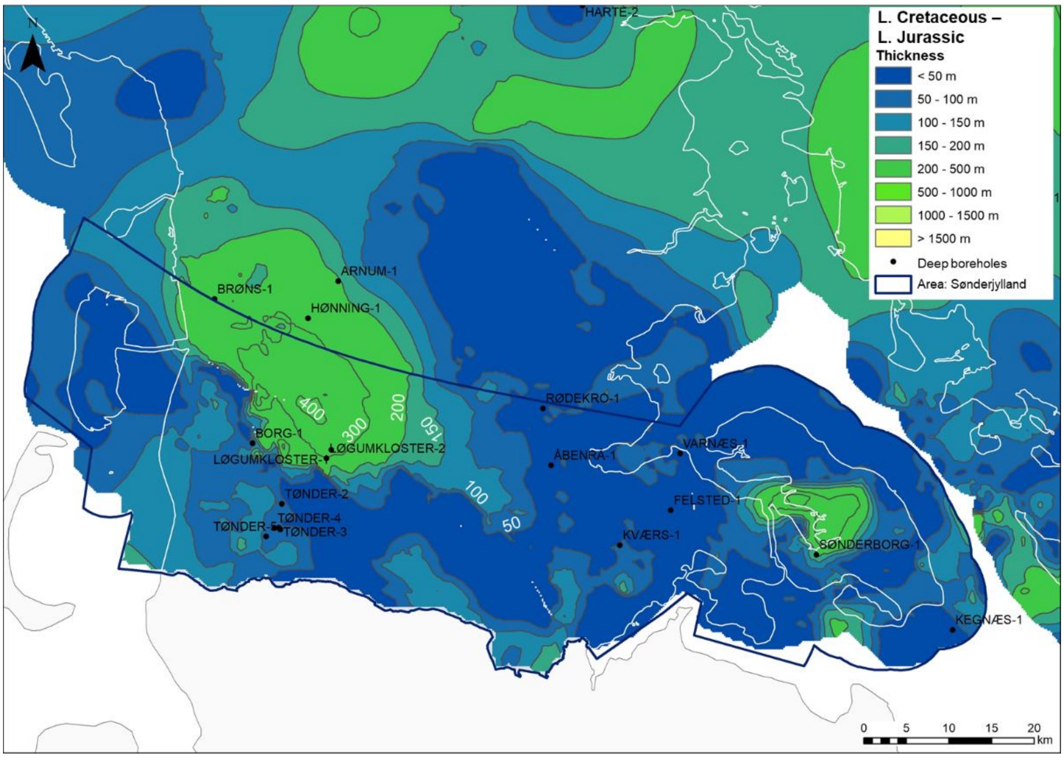


Figure 6.83. *Thickness map of the combined Lower Cretaceous and Jurassic sedimentary successions, Sønderjylland area.*

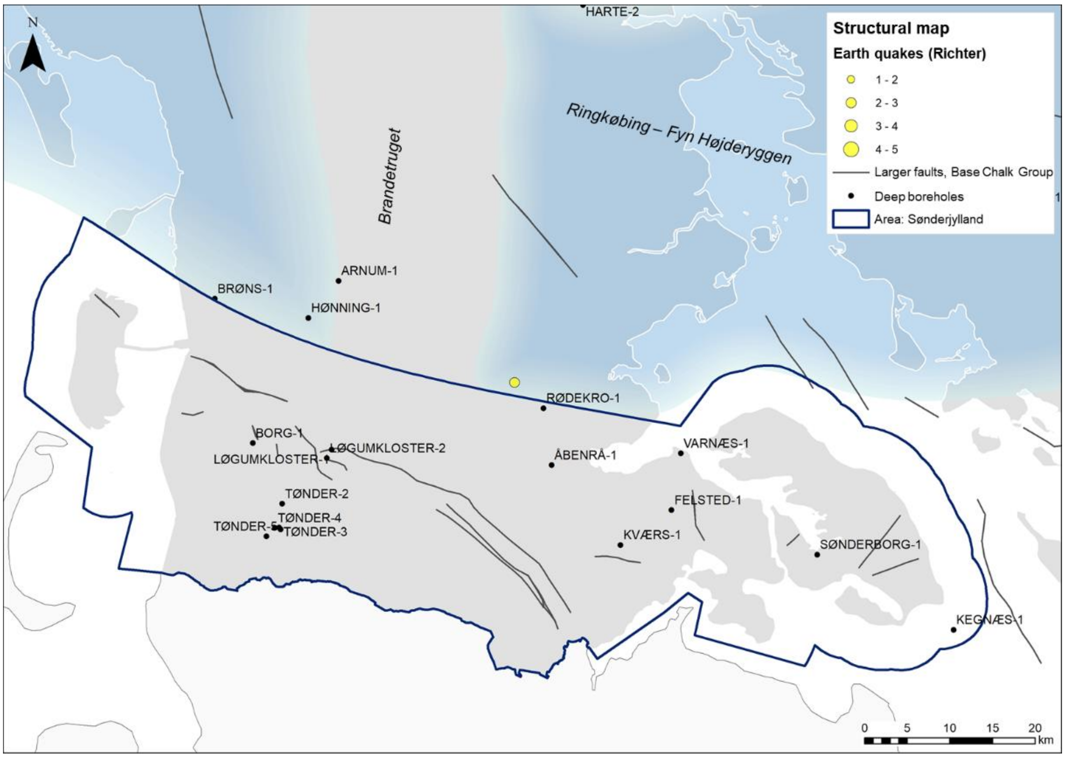


Figure 6.84. *Earthquakes registered during the past 50 years plotted on a structural map, Sønderjylland area. Only one small earthquake has been registered (near the Rødekro-1 borehole).*

Figure 6.85. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Sønderjylland area.*

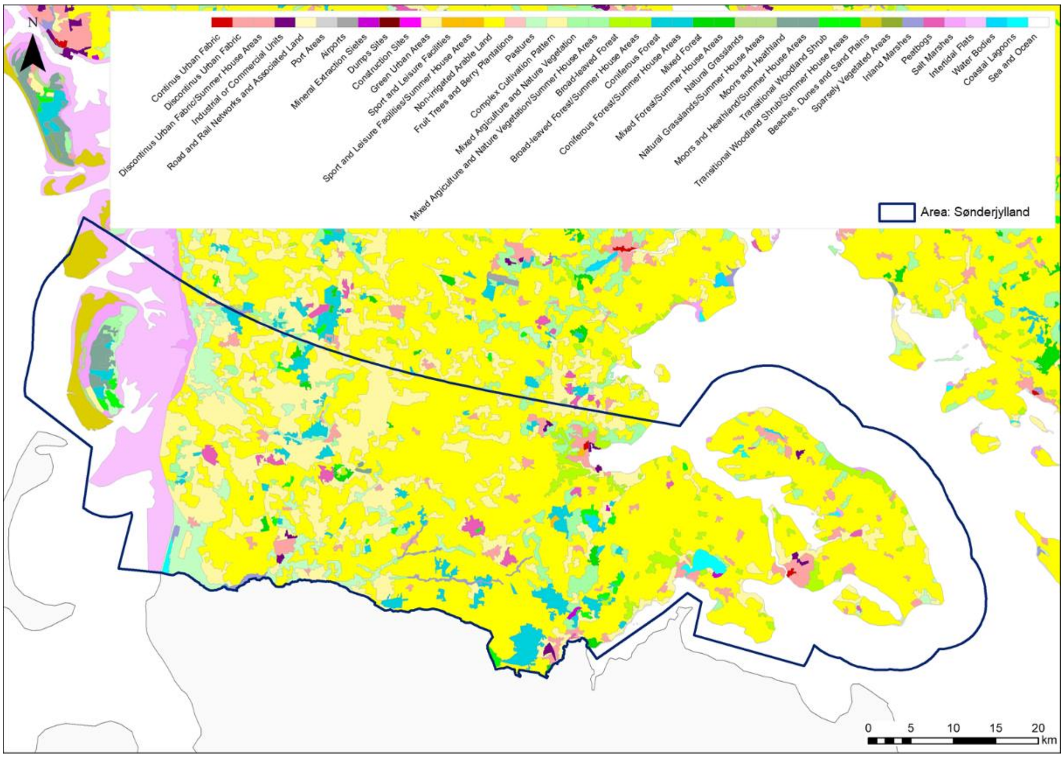


Figure 6.86. *Land use, Sønderjylland area (MiljøGIS, 2021). Large tidal flat areas are present along the west coast (pinkish areas).*

6.7 Fyn

Carbonate constitutes the potential host rock as well as the barriers in the ECZ in the Fyn area. The top of the Chalk Group occurs at depths varying from 0 to 200 meters (Figures 6.89 and 6.90) and the base occurs at 700 meters or deeper (Figure 6.91). The thickness of the carbonate succession generally exceeds 700 meters (Figure 6.95).

The carbonate succession appears to be relatively undisturbed (Figure 4.20). A few large faults have been identified along the southern margin of the Ringkøbing-Fyn High, while small scale faults with very little displacement are seen in the lower part of the Chalk Group (Figures 4.20 and 6.91).

The Fyn area is situated on the tectonically stable Ringkøbing-Fyn High (Figure 6.97). Due to its location in combination with only minor variations in depth to the top of the Chalk Group observed in well logs (Figure 6.88) it is not expected that major faults with large off-sets occur in the central parts of Fyn where the seismic data coverage is sparse (Figures 6.87, 6.90).

Table 6.9. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Fyn area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

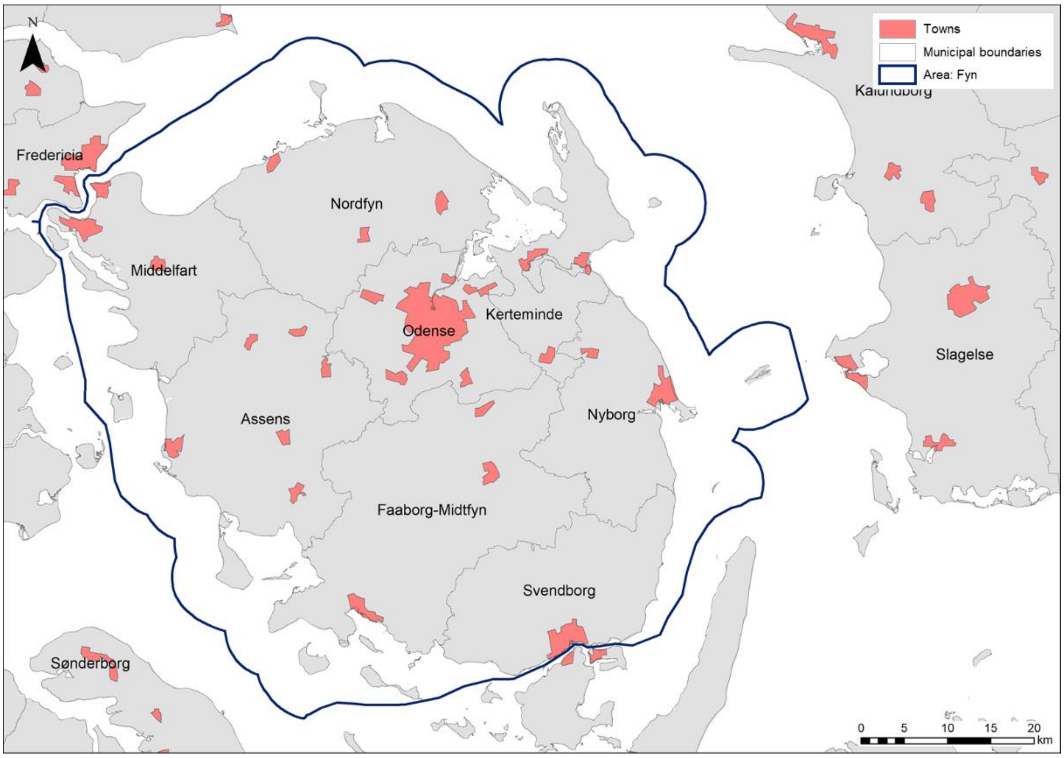


Figure 6.87. *Geographic outline of the Fyn area with towns and municipal boundaries indicated.*

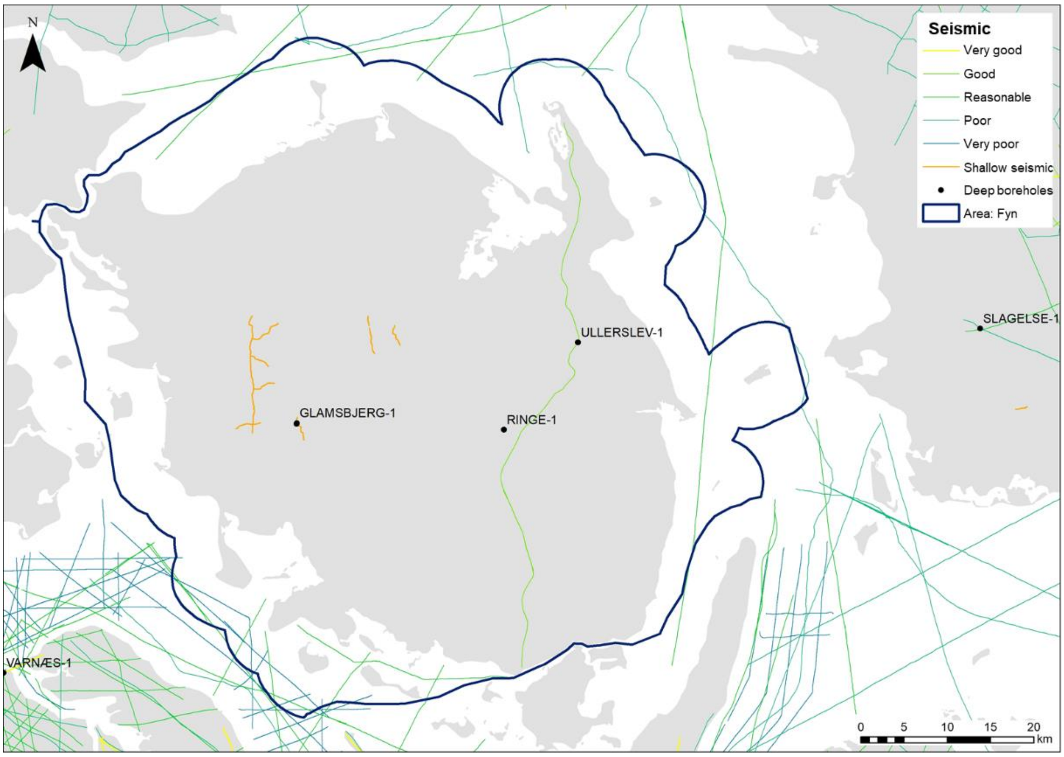


Figure 6.88 *Location map showing seismic lines and their quality, and deep boreholes in the Fyn area. The map illustrates that the seismic coverage is very sparse onshore Fyn, whereas the adjacent offshore areas have a better coverage.*

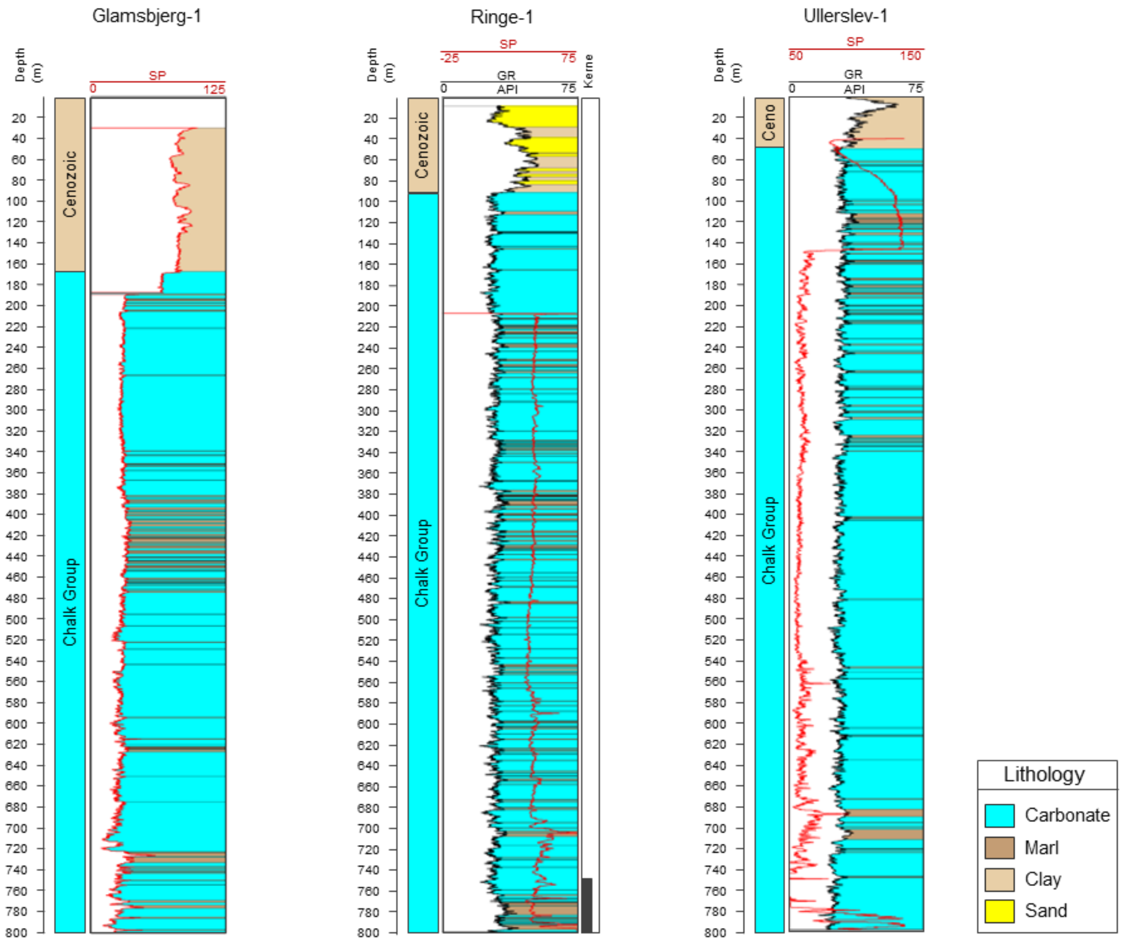


Figure 6.89. *Lithological well log interpretations of the 0–800 meters depth interval of deep boreholes, Fyn area. The Chalk Group carbonate succession comprises interbedded marl layers of varying thickness and frequency. The top of the Chalk Group occurs at depths from approximately 50 meters to 170 meters. Borehole data are applied in the seismic mapping of the top and base of Chalk Group in the Fyn area.*

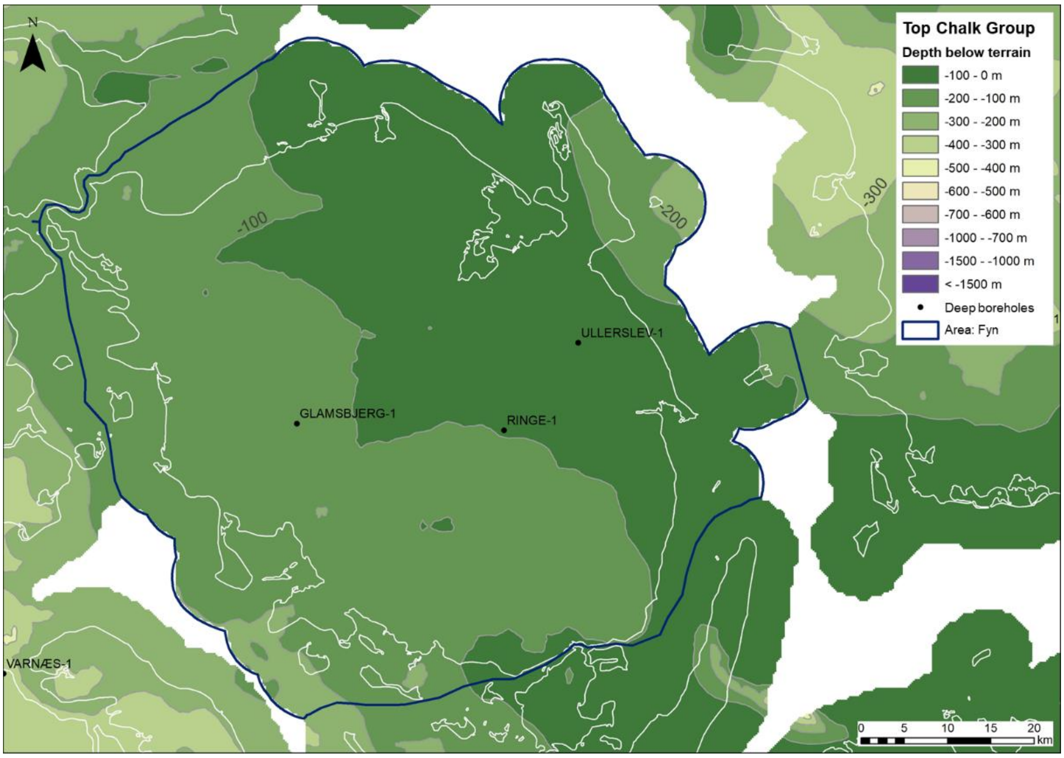


Figure 6.90. *Top Chalk Group depth map, Fyn area. The top of the Chalk Group occurs at depths varying from 0 to 200 meters.*

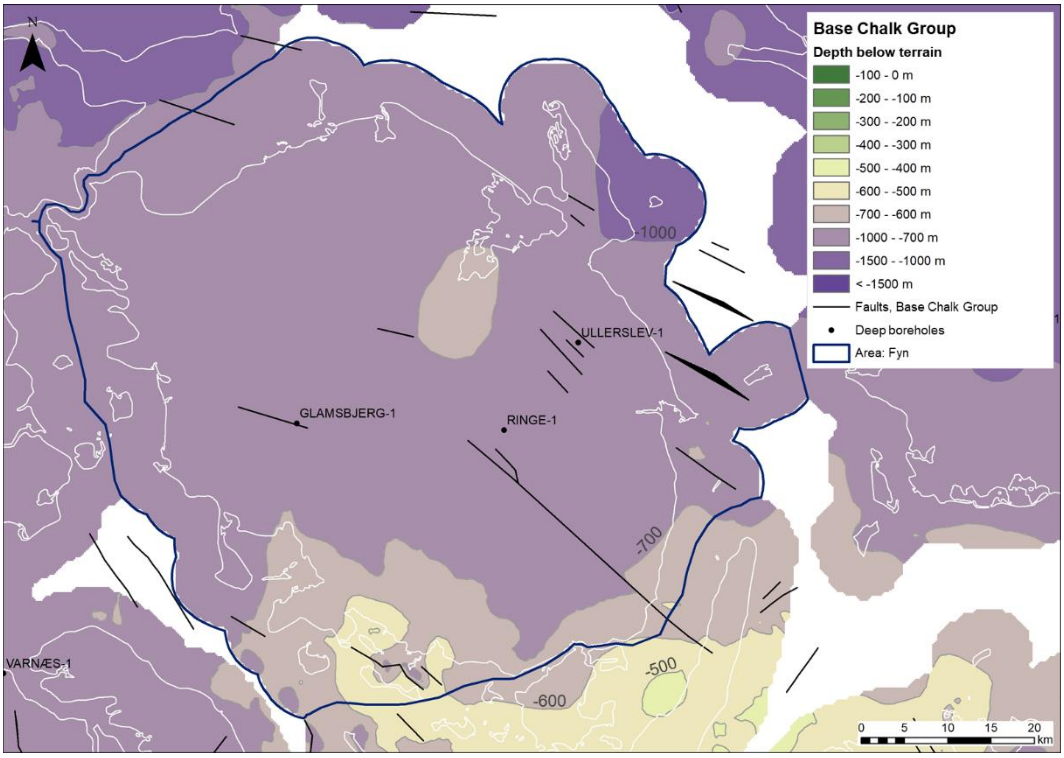


Figure 6.91. *Top Lower Cretaceous (the base of the Chalk Group) depth map, Fyn area. Mapped faults intersecting the base of the Chalk Group are shown. In most of the area, the base of the Chalk Group occurs at depths exceeding 700 meters.*

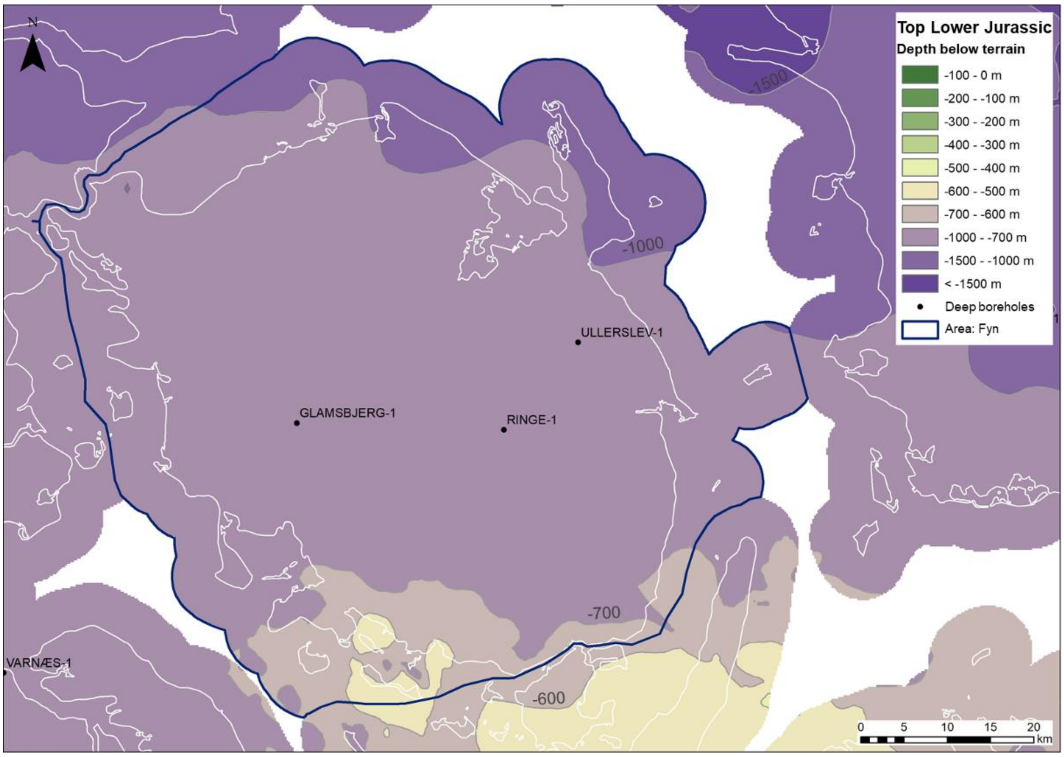


Figure 6.92. *Top Lower Jurassic depth map, Fyn area. The map shows that the Top of the Lower Jurassic occurs at 700 meters or deeper.*

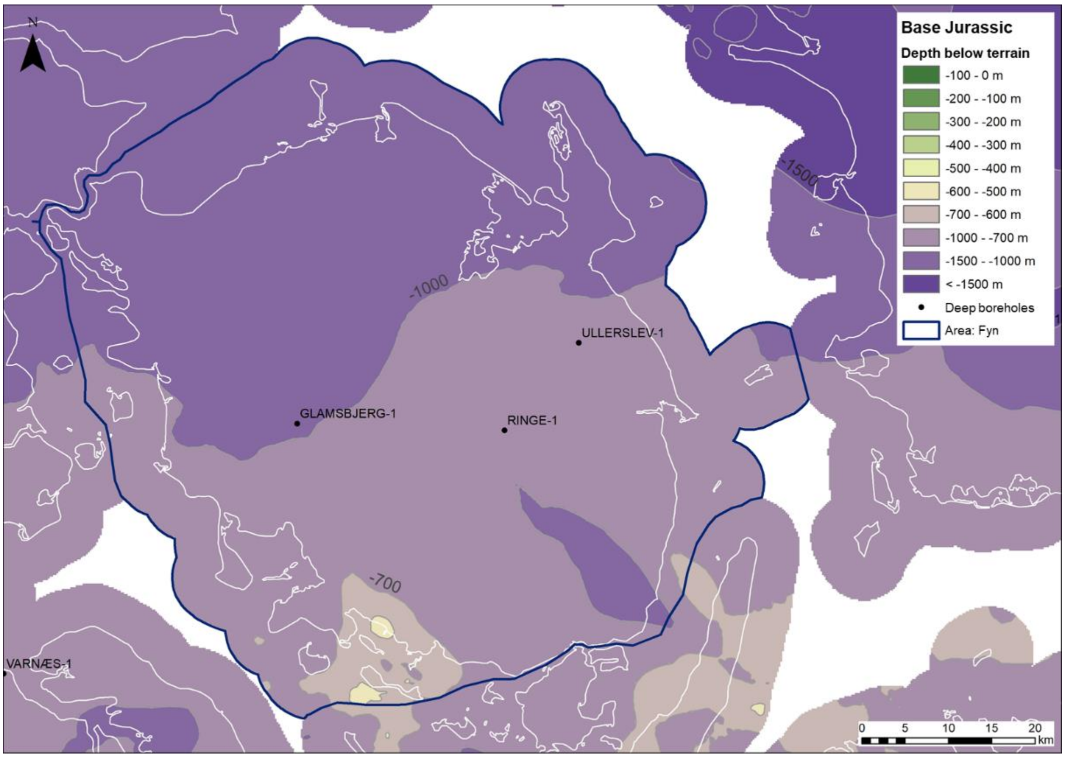


Figure 6.93. *Base Jurassic depth map, Fyn area.*

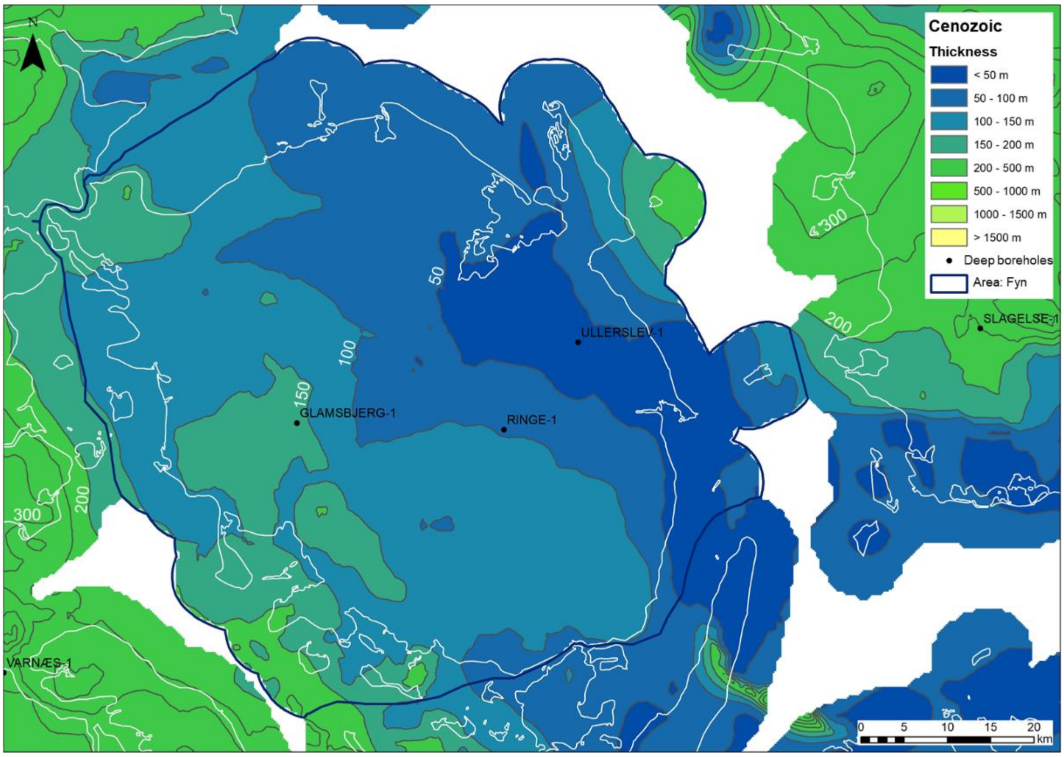


Figure 6.94. *Thickness map of the Cenozoic succession, Fyn area. The map shows thicknesses varying from less than 50 meters in the northeast (dark blue) to 150 meters in the southwest (green).*

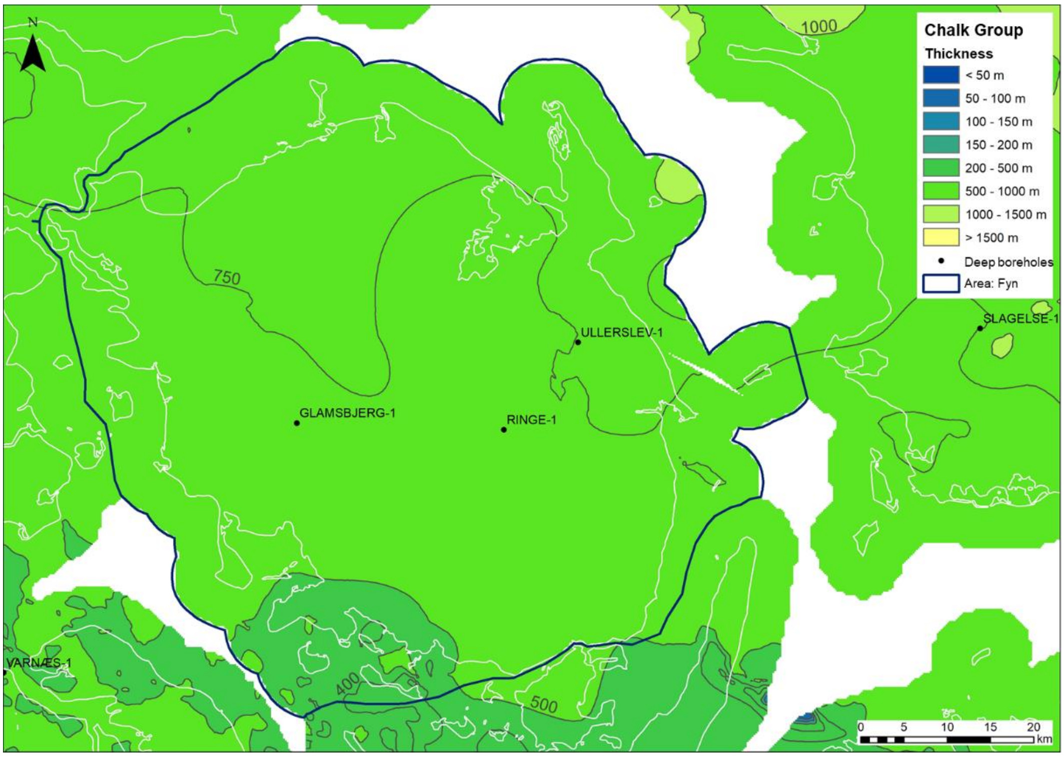


Figure 6.95. *Chalk Group thickness map, Fyn area. The Chalk Group varies in thickness from 500 meters in the southernmost part of the area to more than 750 meters towards the north.*

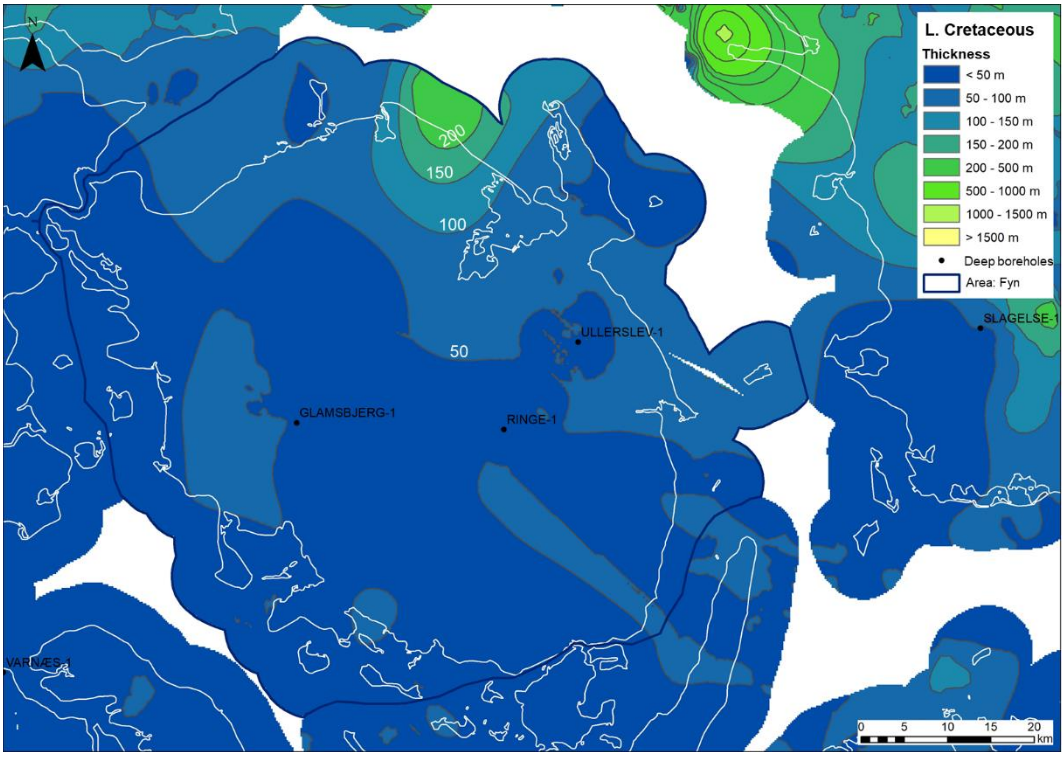


Figure 6.96. *Lower Cretaceous thickness map, Fyn area. The map shows that the Lower Cretaceous section is generally less than 100 meters thick.*

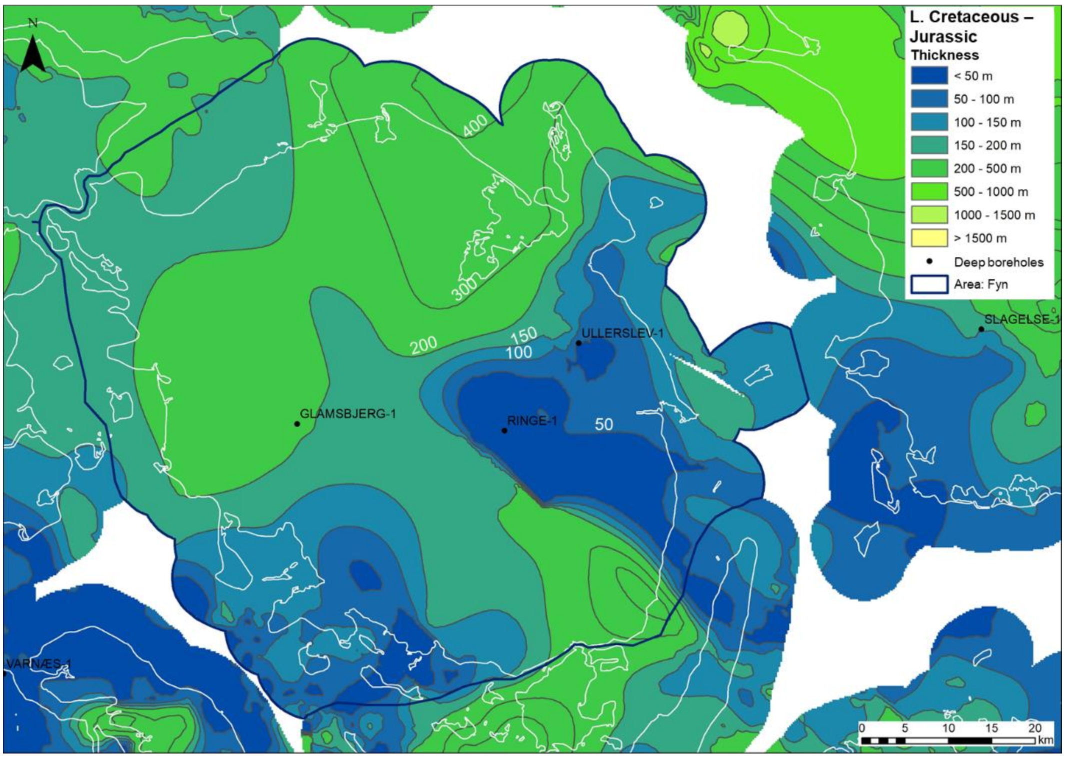


Figure 6.97. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Fyn area.*

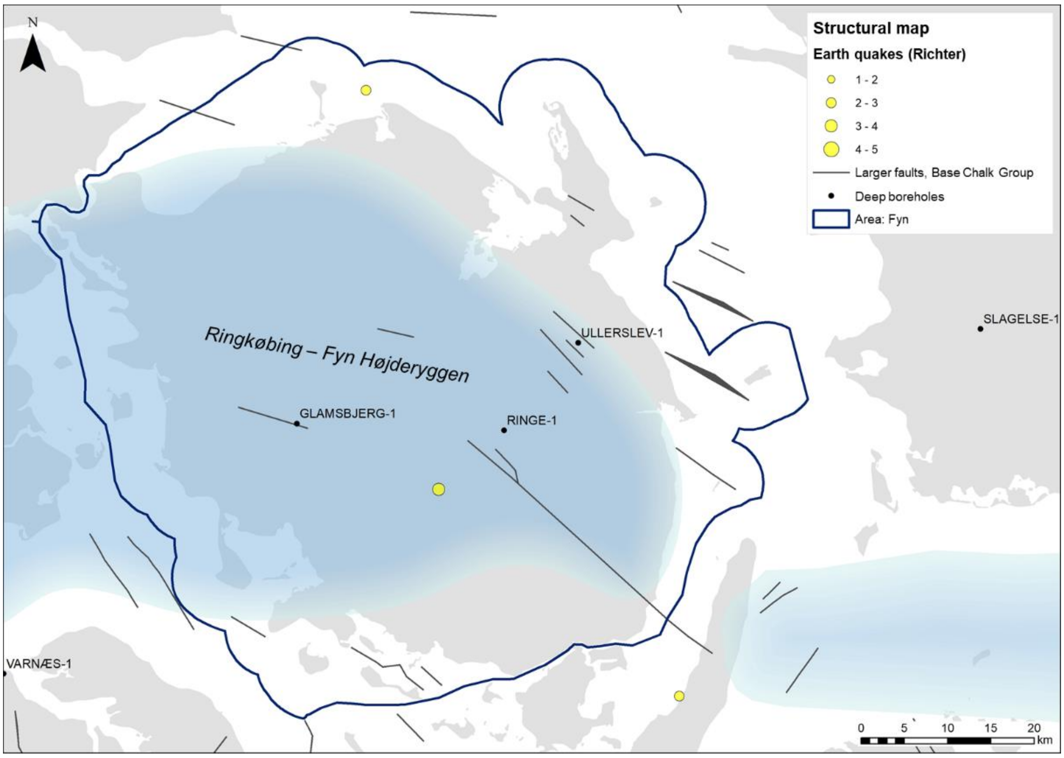


Figure 6.98. *Earthquakes registered during the past 50 years plotted on a structural map, Fyn area. Only a few small earthquakes are registered in and adjacent to the Fyn area.*

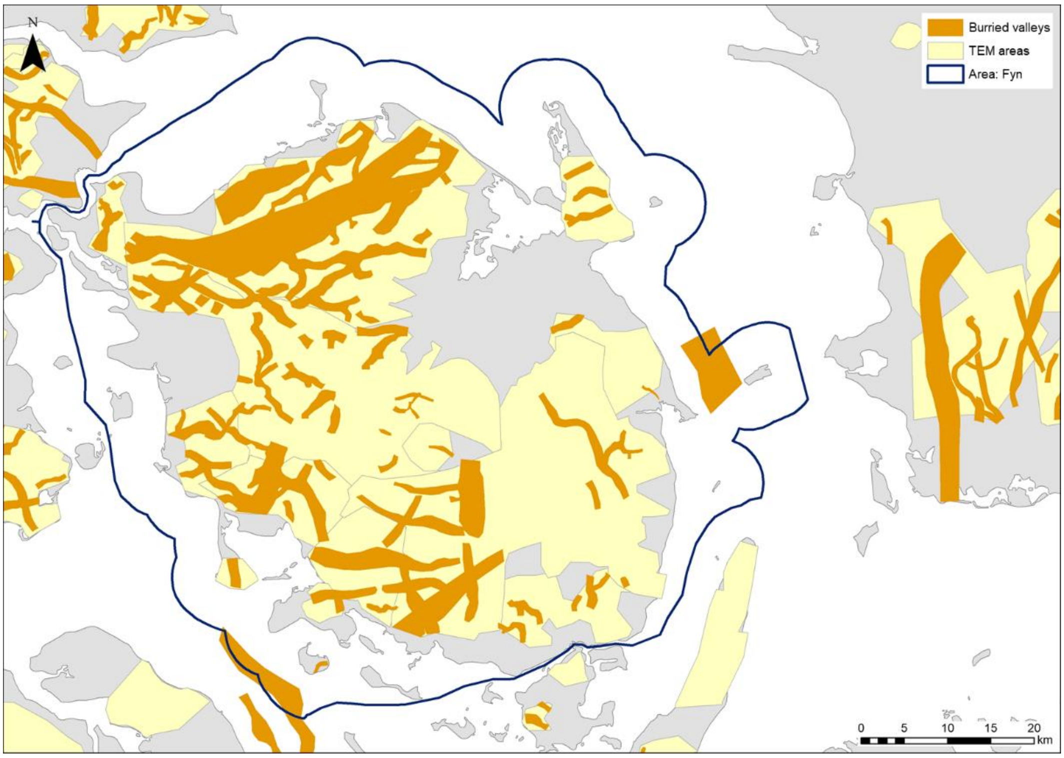


Figure 6.99. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Fyn area.*

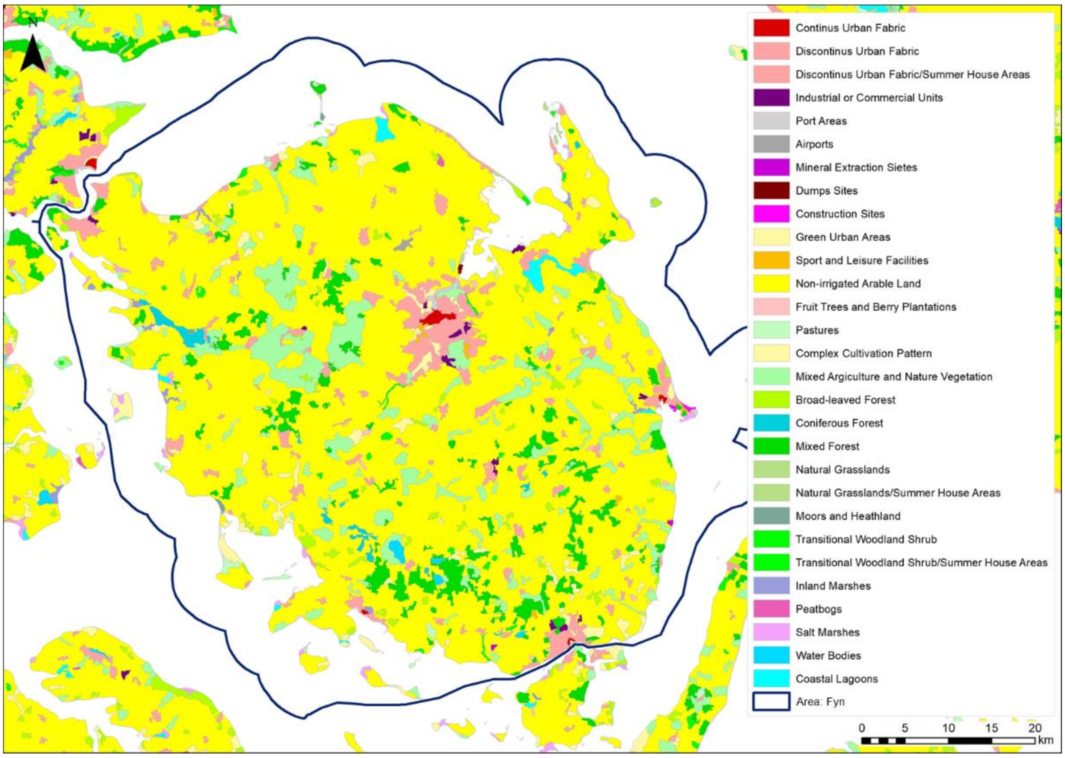


Figure 6.100. *Land use, Fyn area (MiljøGIS, 2021).*

6.8 Sydlige Øhav

In most of the area, carbonate from the Chalk Group occurs in the depth interval from near ground level to 400–500 meters, and therefore carbonate may constitute both a potential host rock as well as a barrier in the ECZ. Claystone from the Lower Cretaceous and Jurassic successions generally occur at depths from 500 meters and deeper, however locally claystone occur at 400–500 meters depth in the eastern part of the area. Thus, there is locally a possibility for claystone successions to provide a potential host rock, and an evaluation has been made for each of the two types of host rock.

The structural framework of the Sydlige Øhav area is illustrated in two cross-sections oriented south – north (Figure 4.21) and west – east (Figure 4.22) respectively. The apparently different geological complexity of the two cross-sections should be noted. In the west–east oriented section (Figure 4.22) the geological layering looks quite uniform, whereas the south–north striking section (Figure 4.21) shows the presence of several fault-bounded half-grabens resulting in large thickness variations of the sedimentary successions over short distances in the north–south orientation across the grabens. The thickness variations of the Lower Cretaceous and Jurassic successions within short distances are also obvious from the map in Figure 6.111.

Claystone host rock (Lower Cretaceous and Jurassic)
The top of the claystone dominated succession (mapped as the base of the Chalk Group) occurs locally at depths of around 400 meters (Figures 6.106 and 6.107). The Lower Cretaceous claystone is laterally widespread, but the thickness is close to, or below seismic resolution and rarely exceeds 50 meters (Figure 6.110). However, the combined total thickness of the Lower Cretaceous and Jurassic claystone successions is of potential interest as a host rock as it may locally exceed 500 meters in the deepest parts of the half-grabens (Figures 6.111 and 4.21).

The thickness of the combined Lower Cretaceous and Jurassic claystone successions varies significantly over short distances from 50 meters to more than 500 meters mainly due to large thickness variations of the Jurassic successions. The horizontal continuity of the claystone sucession (Spatial extent, criterion 1.1) is therefore less suitable and has been given an orange score (Table 6.7). Additionally, the claystone successions described from drill cores comprise numerous interbedded layers of sand and silt (Figures 6.103 and 6.104) and the presence of 100 meters of lithologically homogenous claystone has not been proven.

Sand layers occurring in the underlying Gassum Formation immediately below the Jurassic claystone may act as flow paths which is a less suitable situation for criterion no. 1.4 resulting in an orange score.

Table 6.10 *Evaluation of claystone host rock (Lower Cretaceous and Jurassic), Sydlige Øhav area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

Carbonate host rock (Upper Cretaceous Chalk Group)

Carbonates from the Chalk Group occur extensively in the area, both in the depth interval from 400 to 500 meters and in the overlying ECZ. Carbonates thus provide both a potential host rock and a barrier in the area. The top of the Chalk Group generally occurs at depths from 0 to 100 meters (Figures 6.103, 6.105, and 6.106). The horizontal continuity of the succession varies depending on the size and density of faults. In parts of the area where numerous closely spaced faults occur (Figures 4.21 and 4.22) the horizontal continuity is locally less favourable (Figure 6.113).

The presence of numerous faults in the area results in a variable horizontal continuity of the carbonate section and criterion no. 1.1, regarding the spatial extent, is given a yellow score (potentially suitable).

The base of the Chalk Group generally occurs at depths varying between 500 and 600 meters. Sand layers in the Lower Cretaceous and Jurassic claystone successions may act as flow paths and have been recognized immediately below the carbonate successions (Figure 6.103) i.e., close to the depth of interest for deep disposal. In case a site with a potential carbonate host rock is chosen for detailed investigation, emphasis should be put on investigating the potential presence of sand layers immediately below the host rock interval, so mitigating actions can be taken if potential flow paths are present.

Table 6.11. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Sydlige Øhav area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

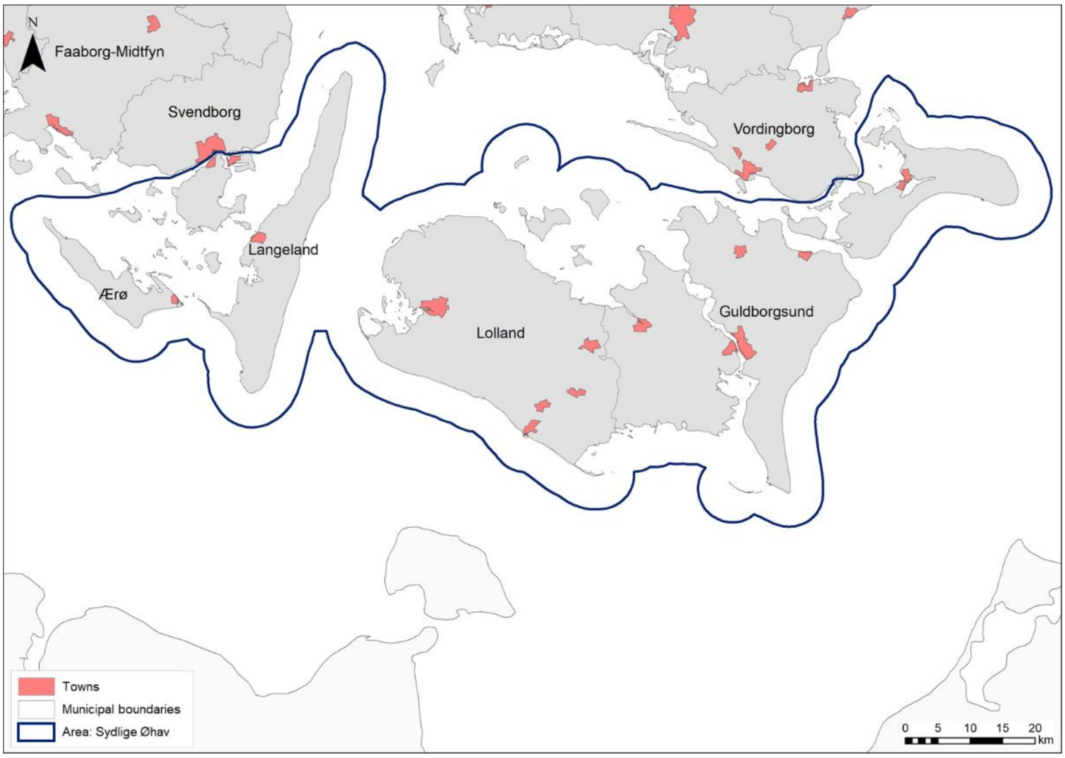


Figure 6.101. *Geographic outline of the Sydlige Øhav area with towns and municipal boundaries indicated.*

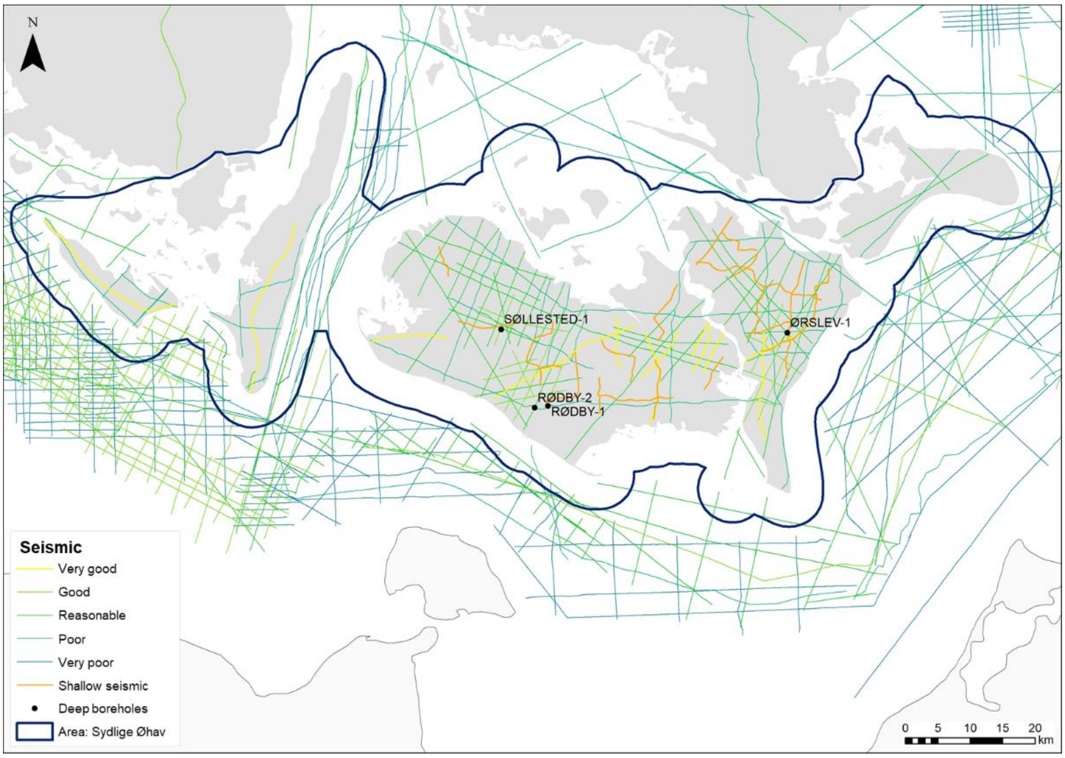


Figure 6.102.*, Location map showing seismic lines and their quality, and deep boreholes in the Sydlige Øhav area. The map shows that numerous seismic lines exist in the area and adjacent offshore areas.*

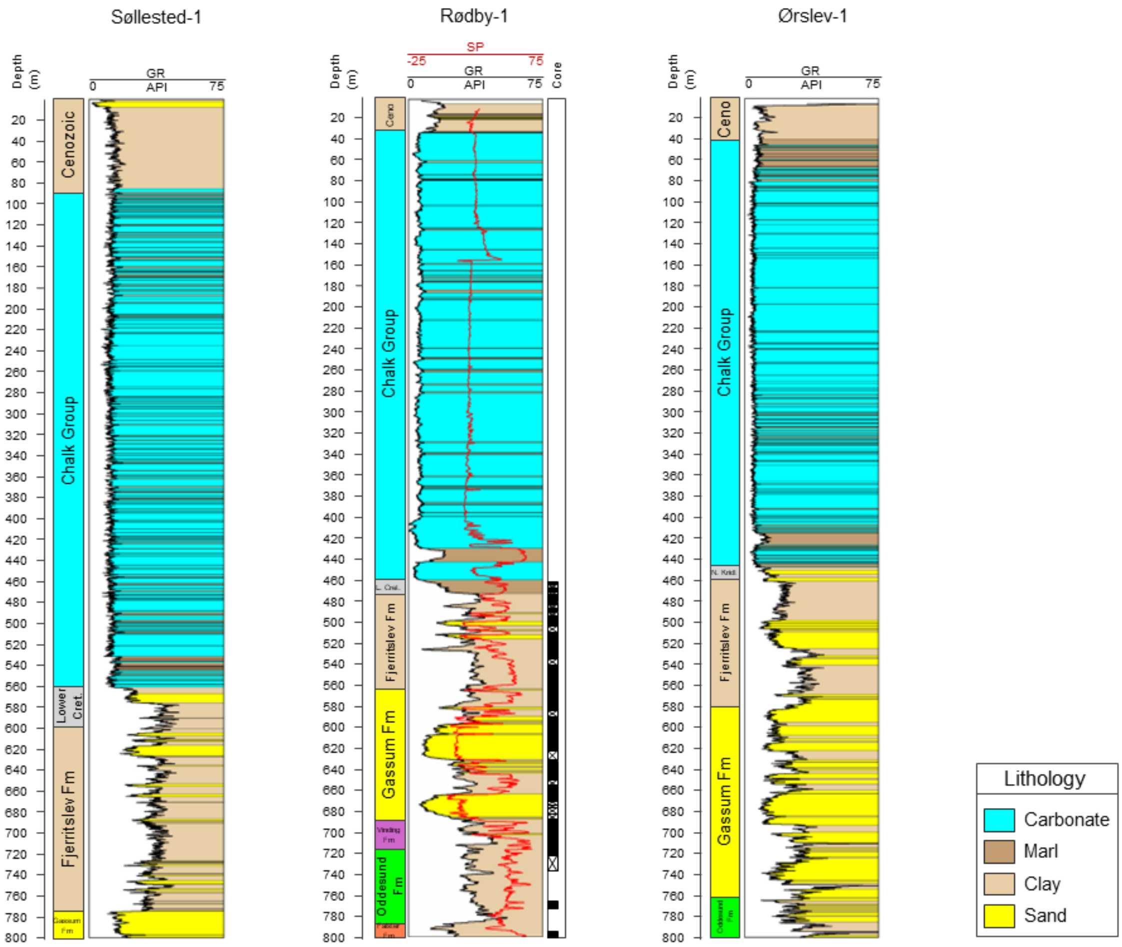


Figure 6.103. *Lithological well log interpretations of the 0-800 meters depth interval from deep boreholes in the Sydlige Øhav area. The logs show that carbonate from the Chalk Group constitutes the depth interval from near surface (30–80 meters) to depths ranging from 440 meters to 550 meters. Below this, Lower Cretaceous and Lower Jurassic sediments consisting of alternating sand and claystone layers are present. The thickest claystone intervals identified (without sand) are approximately 30–40 meters thick. Note that the transition from the Gassum Formation sandstone to the overlying Fjerritslev Formation claystone is gradational with an upwards decreasing frequency of sand layers. As a result, the seismic mapping of the base Jurassic (base Fjerritslev Fm) is associated with uncertainty due to the lack of a sharp lithological boundary.*

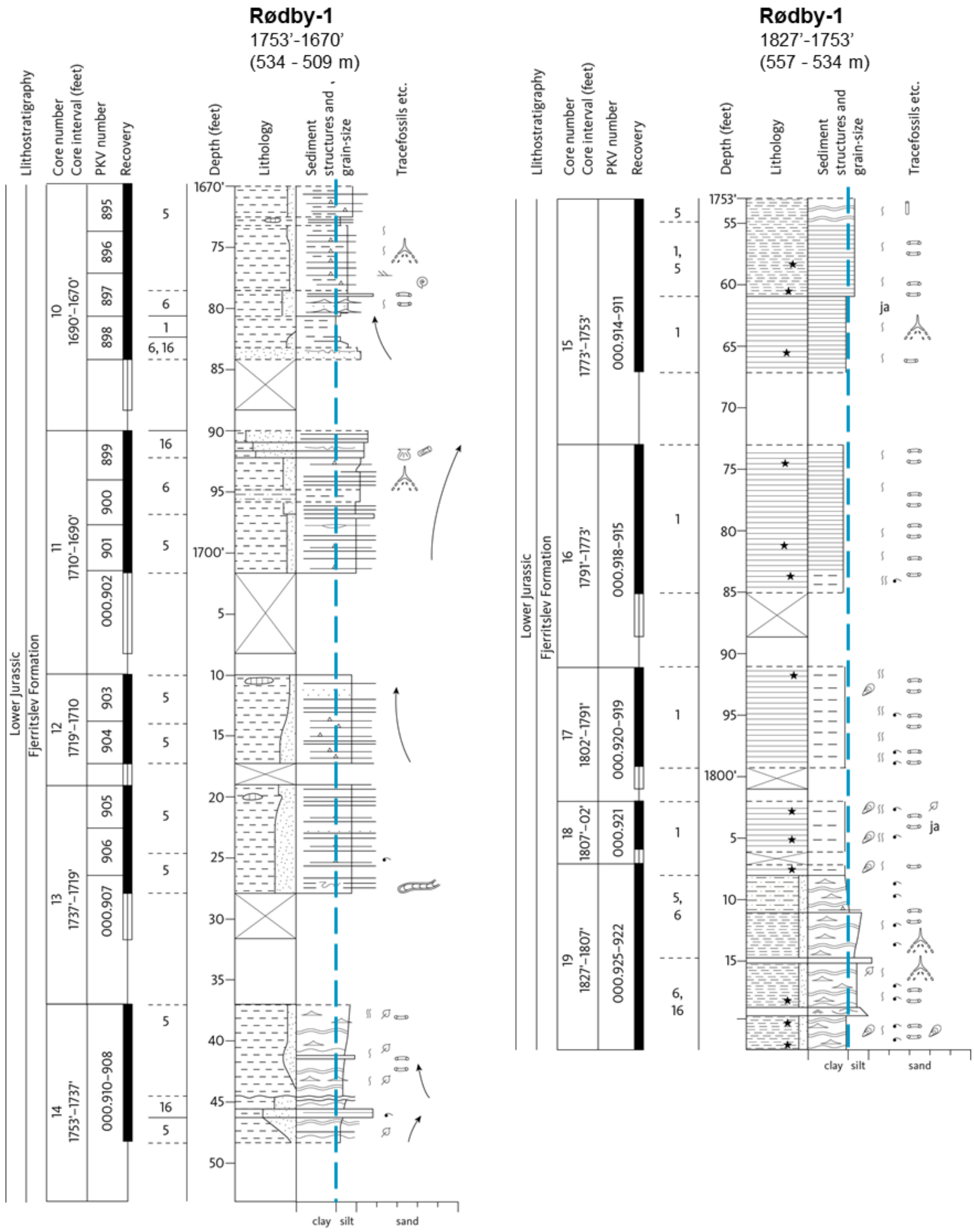


Figure 6.104. *Representative sedimentological logs from the Lower Jurassic successionn in the Rødby-1 borehole, Sydlige Øhav area. The dotted blue line highlights the boundary between clay (to the left) and silt and sand grain sizes (to the right). The figure shows that the Fjerritslev Formation is lithologically inhomogeneous due to the varying grain size of the layers. A homogenous claystone section is identified from 1762' to 1808' on the log to the right corresponding to a thickness of around 15 meters.*

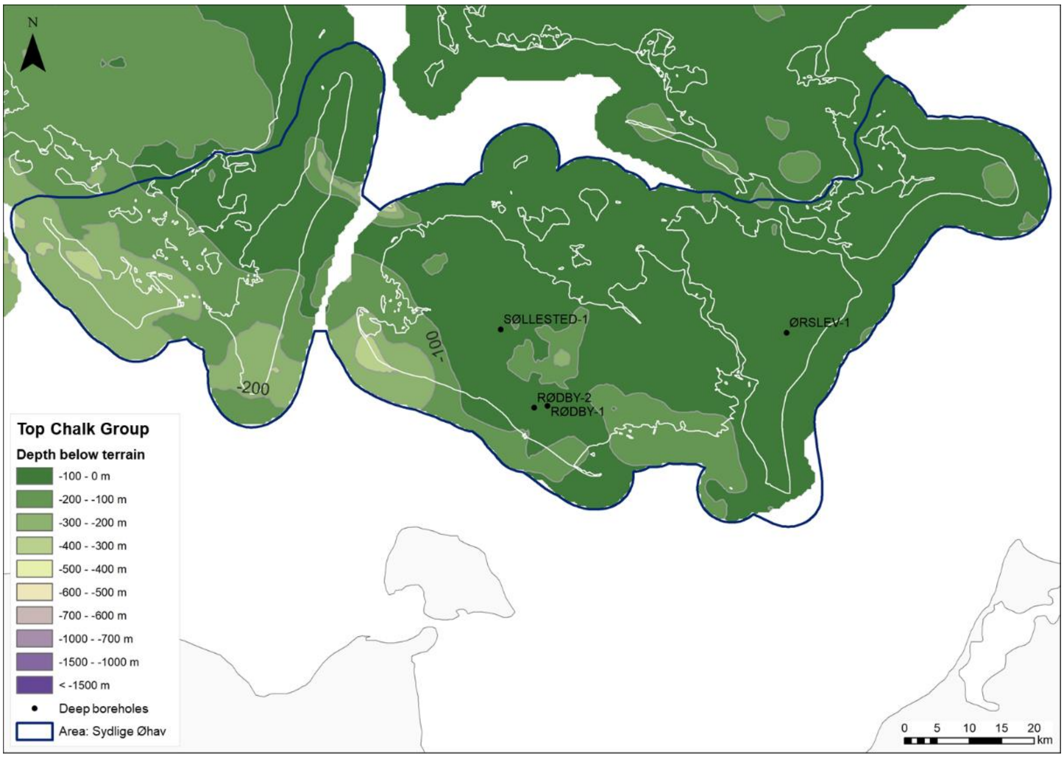


Figure 6.105. *Top Chalk Group depth map, Sydlige Øhav area. The map shows that the top of the Chalk Group generally occurs at depths shallower than 100 meters.*

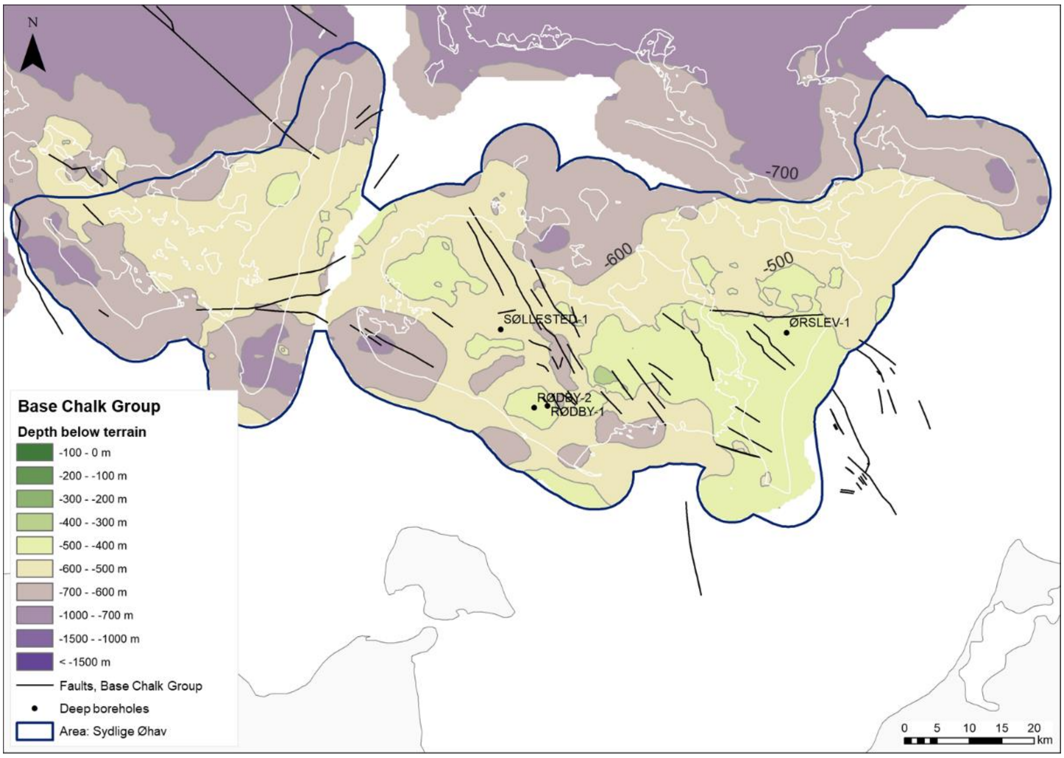


Figure 6.106. *Top Lower Cretaceous (base of the Chalk Group) depth map, Sydlige Øhav area. Mapped faults intersecting the base of the Chalk Group are shown. The depth varies between 400 and 600 meters over relatively short distances. This is due to salt remobilization and the presence of deeper lying salt structures.*

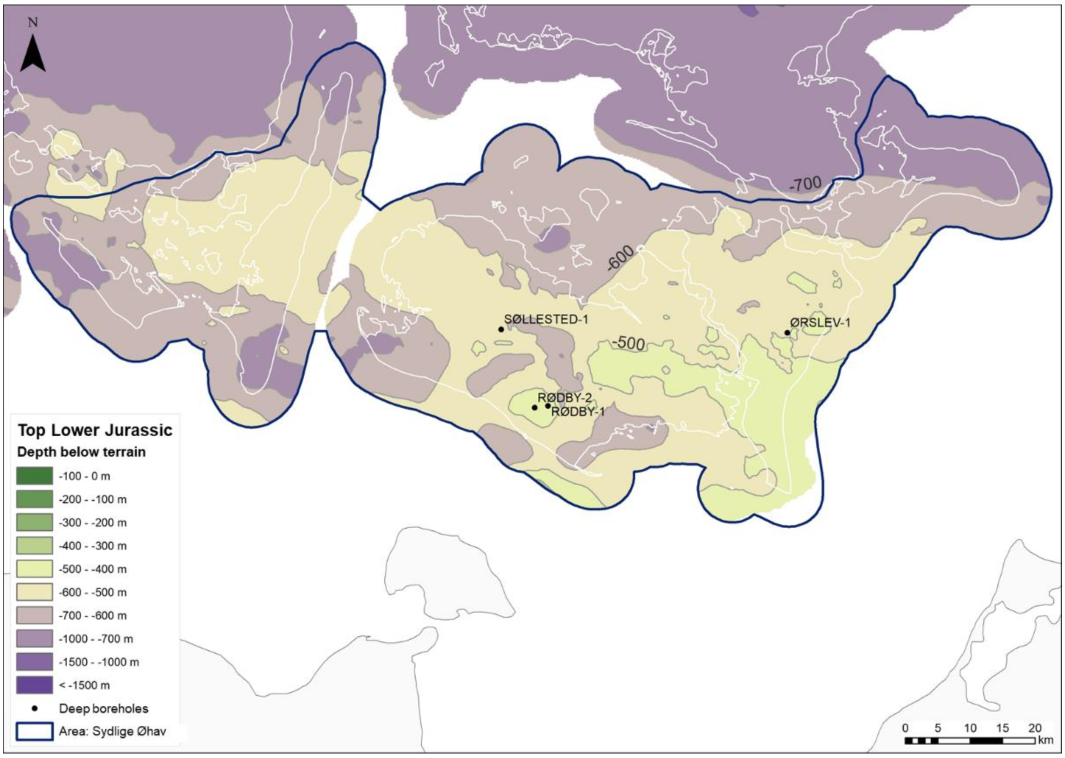


Figure 6.107. *Top Lower Jurassic depth map, Sydlige Øhav area. In most of the area, the depth to Top Lower Jurassic is 500–600 meters, locally as deep as 700 meters.*

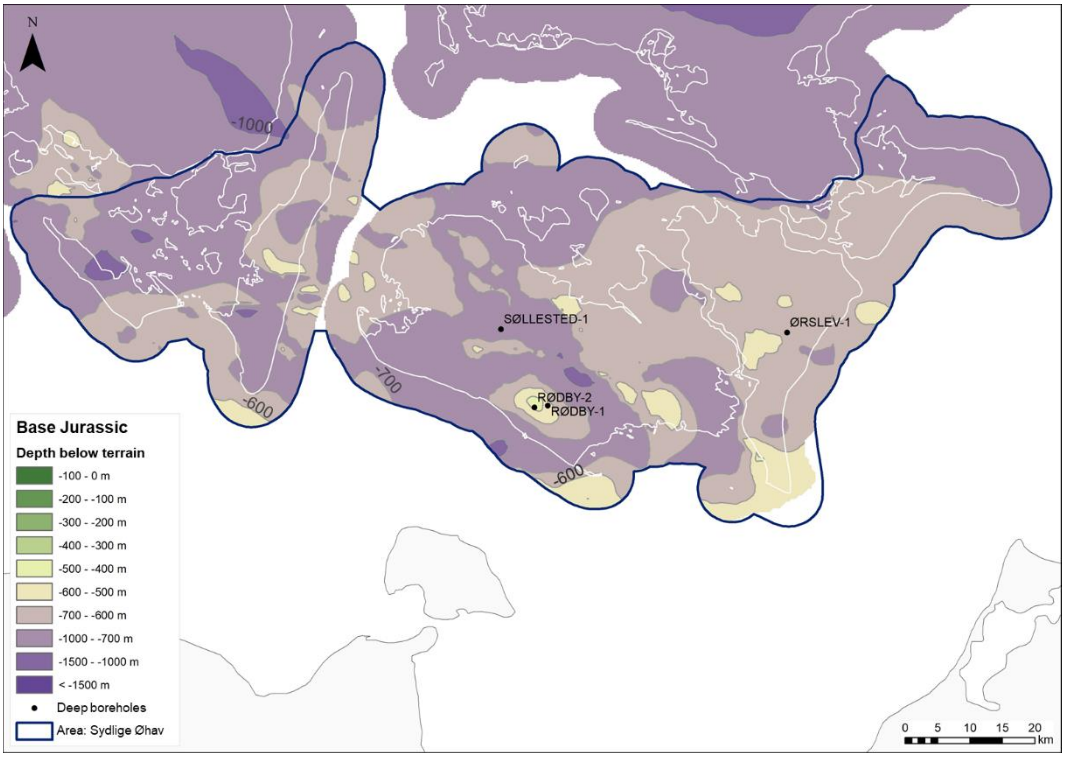


Figure 6.108. *Base Jurassic depth map, Sydlige Øhav, showing the depth varies from 500 to more than 700 meters, and, locally, to 1000 meters. The irregular contour pattern in this area is due to the presence of fault-bounded half-grabens filled by Jurassic sediments and the presence of salt structures (Figure 4.21).*

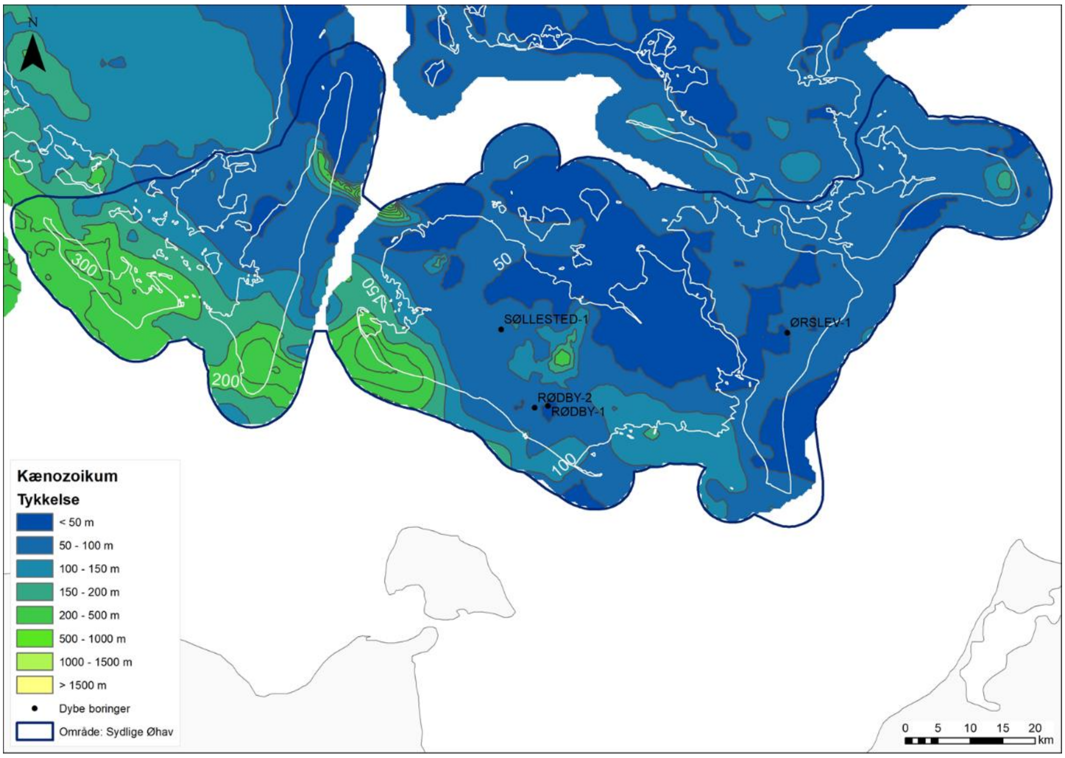


Figure 6.109. *Cenozoic thickness map, Sydlige Øhav area. The map shows that the Cenozoic succession varies in thickness from 0 to 100 meters.*

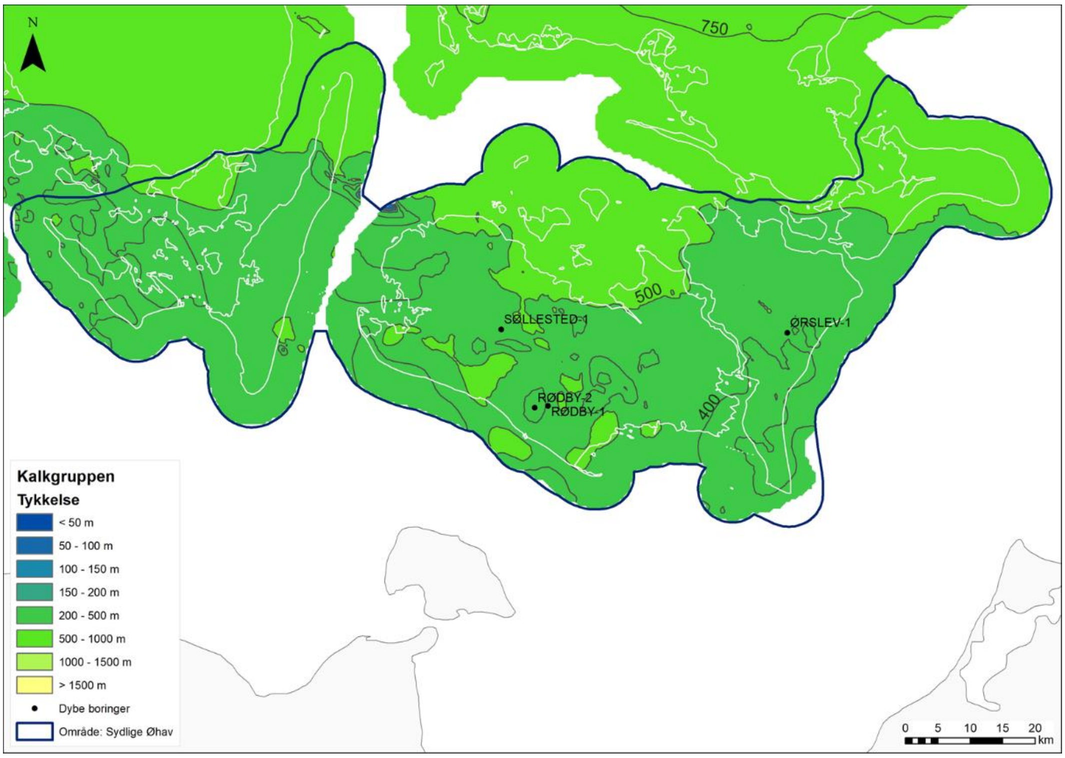


Figure 6.110. *Chalk Group thickness map, Sydlige Øhav area. The map shows that the carbonate thickness in the area is generally around 400 and 500 meters.*

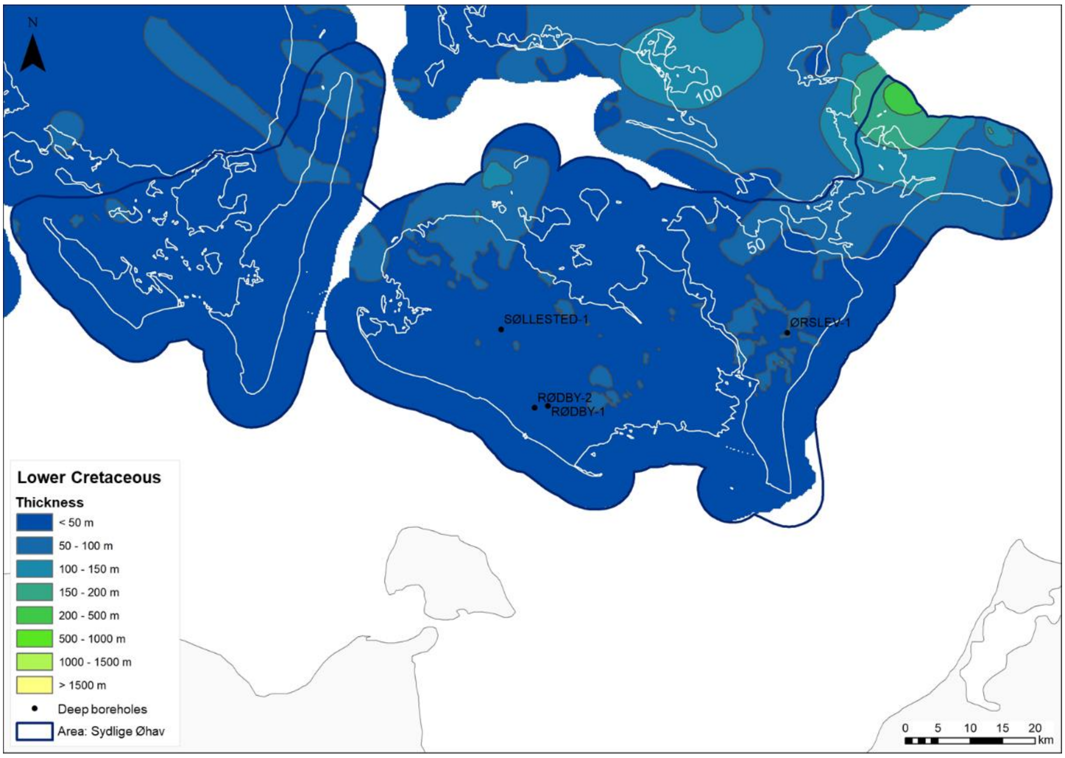


Figure 6.111. *Lower Cretaceous thickness map, Sydlige Øhav area. The map shows that the Lower Cretaceous succession is generally thin and rarely exceeds 50 meters.*

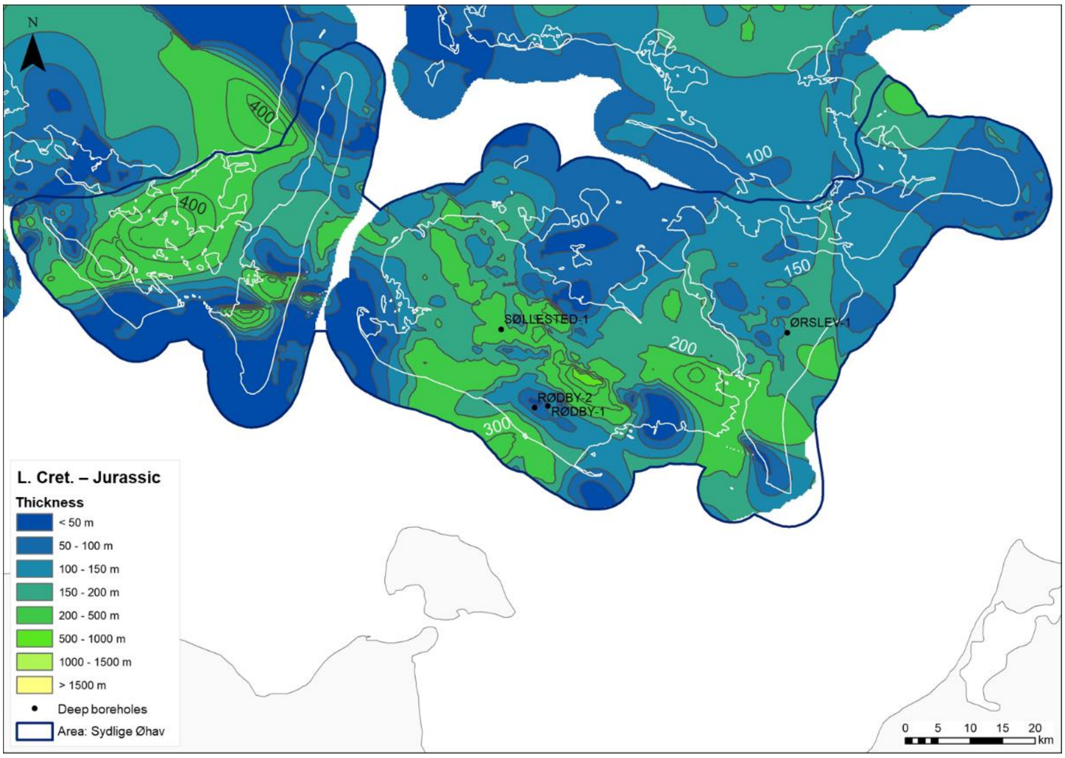


Figure 6.112. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Sydlige Øhav area. The thickness varies between 50 and 500 meters over short distances due to the Lower Jurassic successions occurring in fault-bounded half grabens (Figure 4.21).*

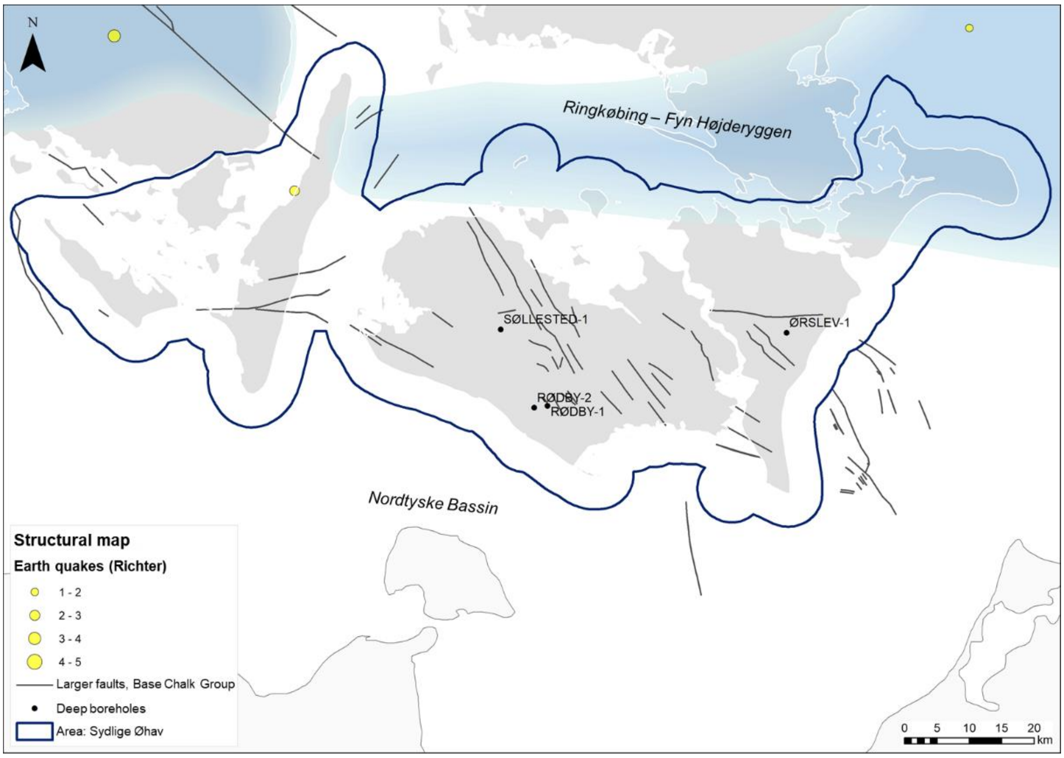


Figure 6.113. *Earthquakes registered during the past 50 years plotted on a structural map, Sydlige Øhav area. Very few earthquakes are registered in, and adjacent to the area.*

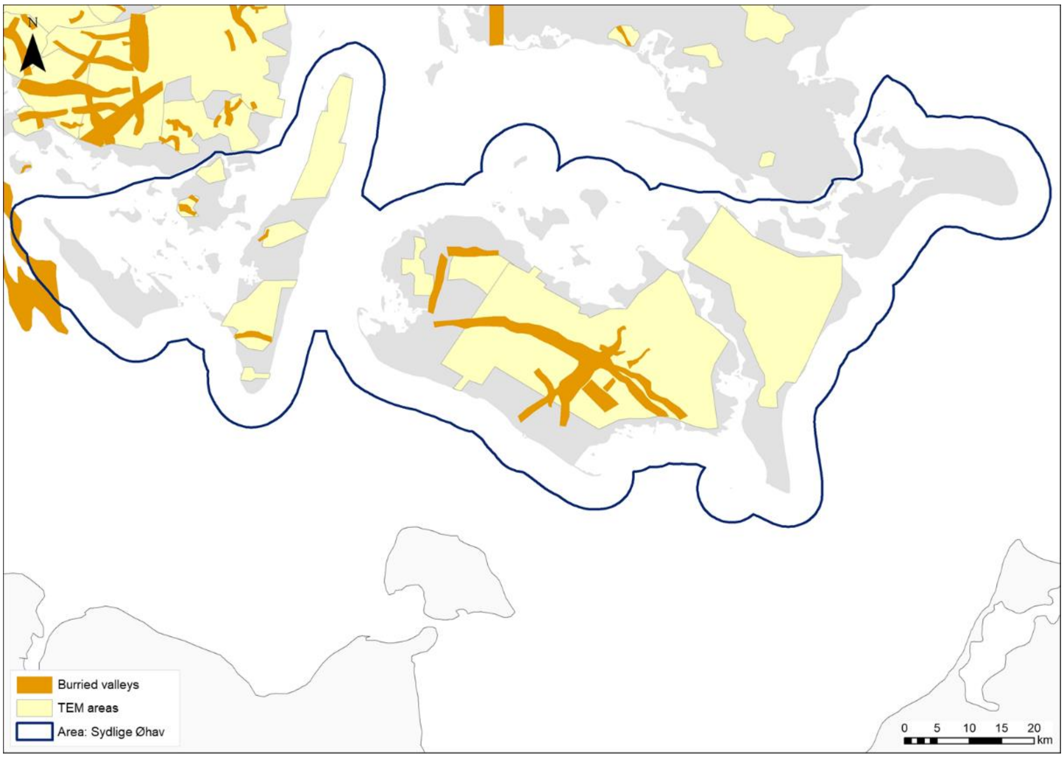


Figure 6.114. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Sydlige Øhav area. Most of the area is covered by TEM surveys and in large parts of the area buried valleys have not been identified.*

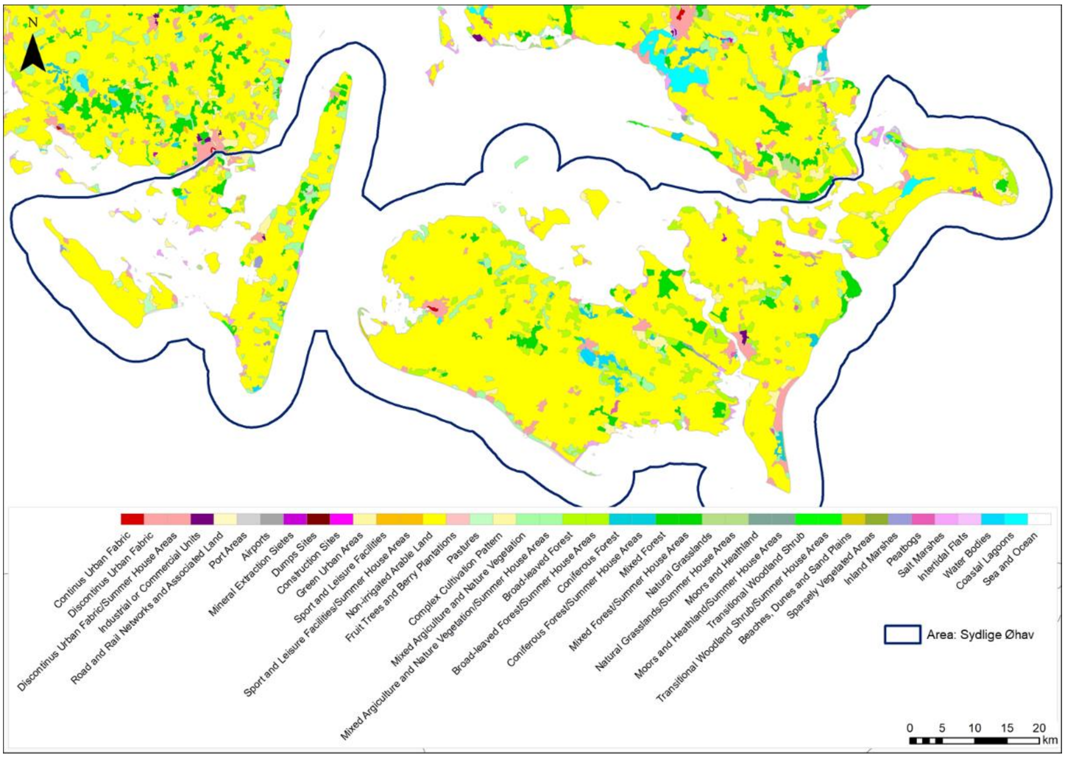


Figure 6.115. *Land use, Sydlige Øhav area. (MiljøGIS, 2021).*

6.9 Sydvestsjælland

Carbonates from the Chalk Group occur in the 400–500 meters depth interval and the carbonate section has a thickness varying between 500 and 1000 meters throughout the area (Figures 4.23, 4.24, 6.119, and 6.124). Carbonates thus provide a potential host rock and a potential barrier with thicknesses generally exceeding 250 meters in the ECZ. To the northeast, however, the top of the Chalk Group occurs as deep as 450 meters below surface (Figures 6.119 and 6.124) and is overlain by Cenozoic sandy sediments. Thus, in this part of the area the carbonate thickness is less than 100 meters in the ECZ and does not fulfill the 250 meters thickness requirement for criterion 1.1 (Figure 6.118).

Locally, in the northeastern part of the Sydvestsjælland area (around the Isefjord inlet), numerous earthquakes have been recorded (Figure 6.127). The natural stability in this part of the area (criterion 2.1) may be compromised in case further displacement takes place along the fault planes. However, most of the area has only little seismic activity and sites with faults can be avoided by detailed seismic mapping.

The carbonates continue to great depths (700–1500 meters, Figure 6.120). Therefore, in the areas where the top of the Chalk Group is located relatively deeply, a 250 meters carbonate section in the ECZ can be achieved if a repository is placed deeper than 500 meters.

Table 6.12. *Evaluation of carbonate host rock (Chalk Group Upper Cretaceous), Sydvestsjælland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

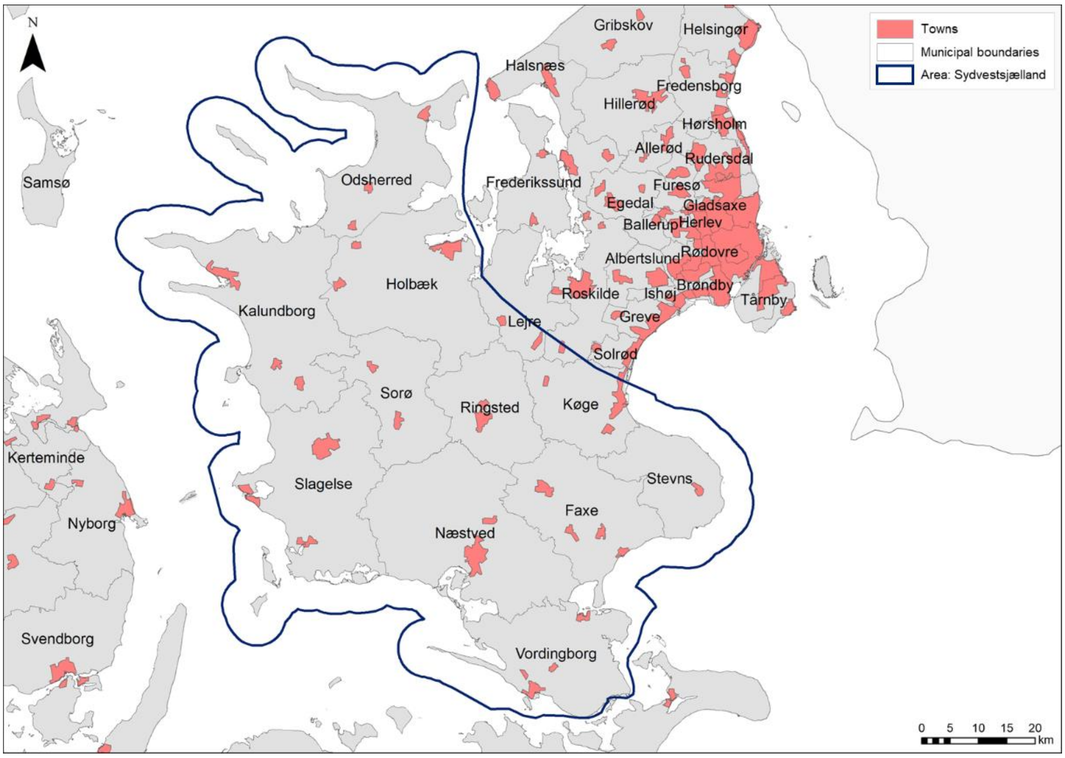


Figure 6.116. *Geographic outline of the Sydvestsjælland area with towns and municipal boundaries indicated.*

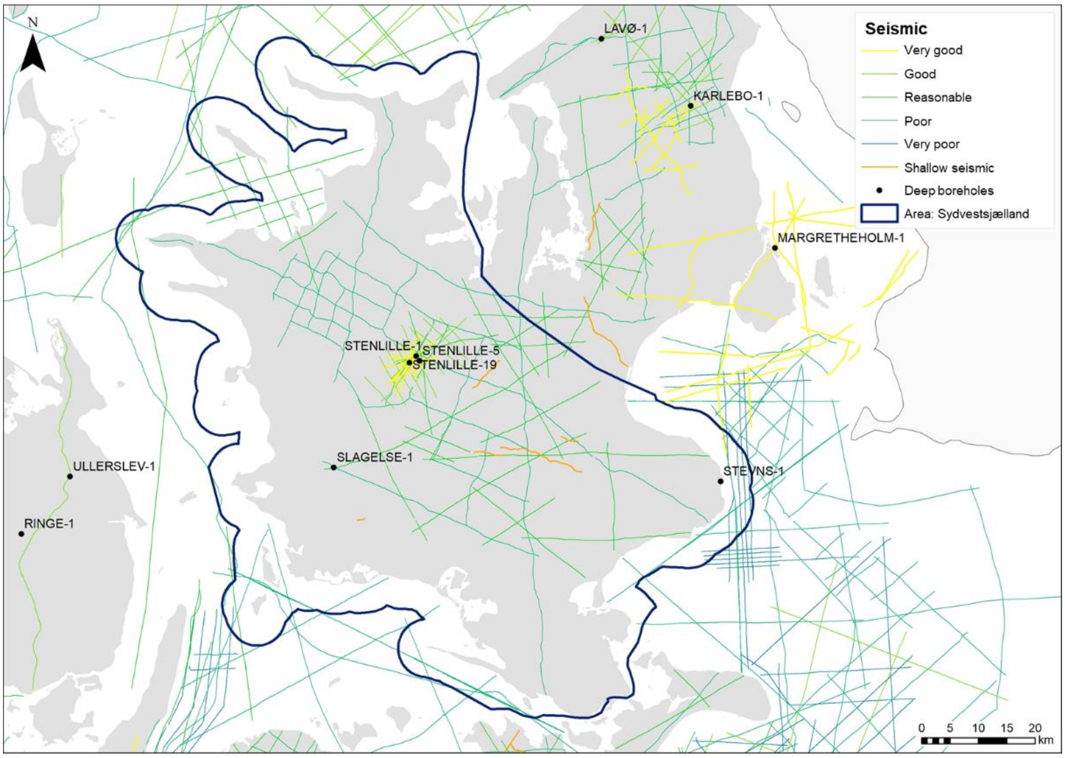


Figure 6.117. *Location map showing seismic lines and their quality, and deep boreholes, Sydvestsjælland area. In the central part of the area, there is a relatively high density of seismic data which was acquired for mapping prior to gas storage in the Stenlille area.*

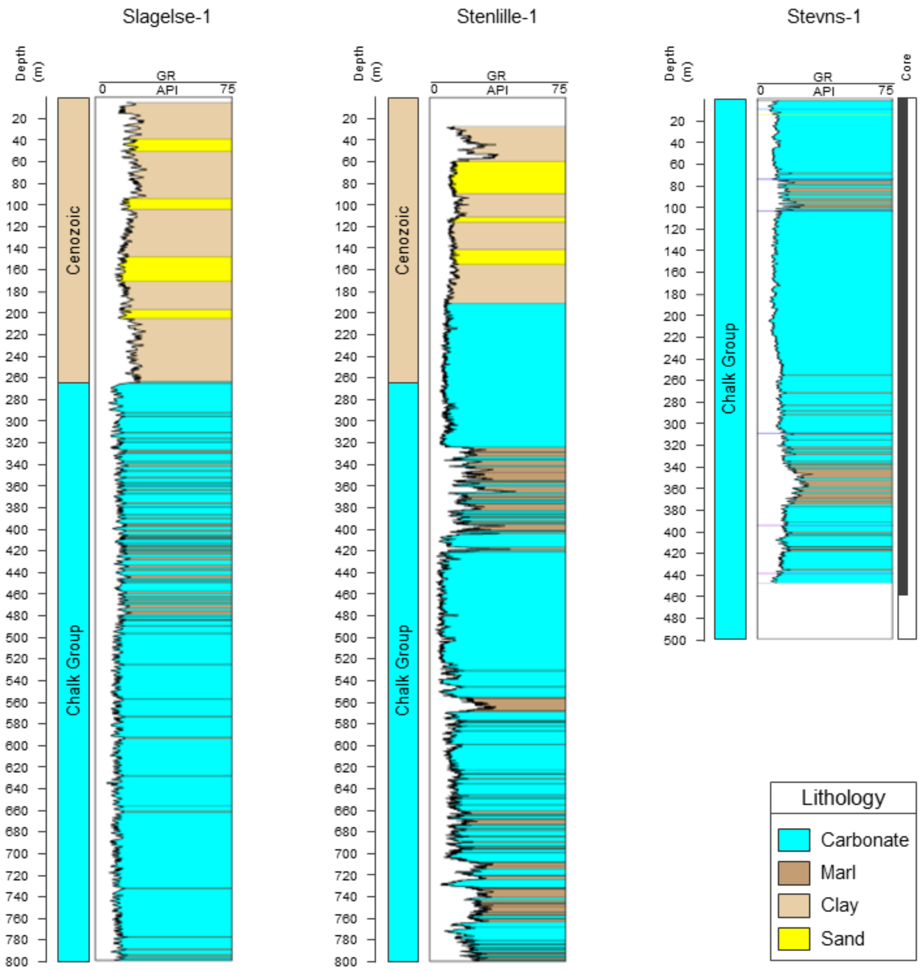


Figure 6.118. *Lithological well log interpretations of the 0–800 meters interval from deep boreholes in the Vestsjælland area. The figure illustrates that the top of the carbonate succession (Chalk Group) occurs at depths varying from 0 meters (terrain) to approximately 260 meters in the Slagelse-1 well. The carbonate succession continues to depths exceeding 800 meters and contains several intervals dominated by marl.*

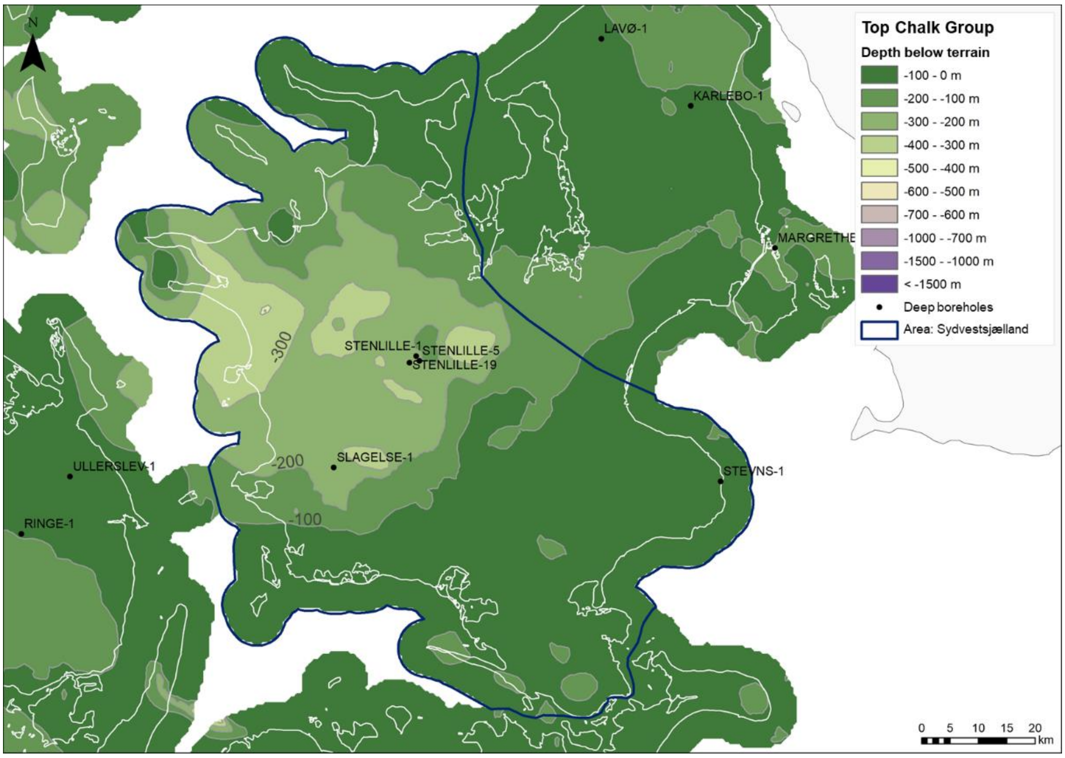


Figure 6.119. *Top Chalk Group depth map, Sydvestsjælland area. The depth to the top of the Chalk Group varies from 0 to 300 meters and is deepest in the western part of the area (light green areas).*

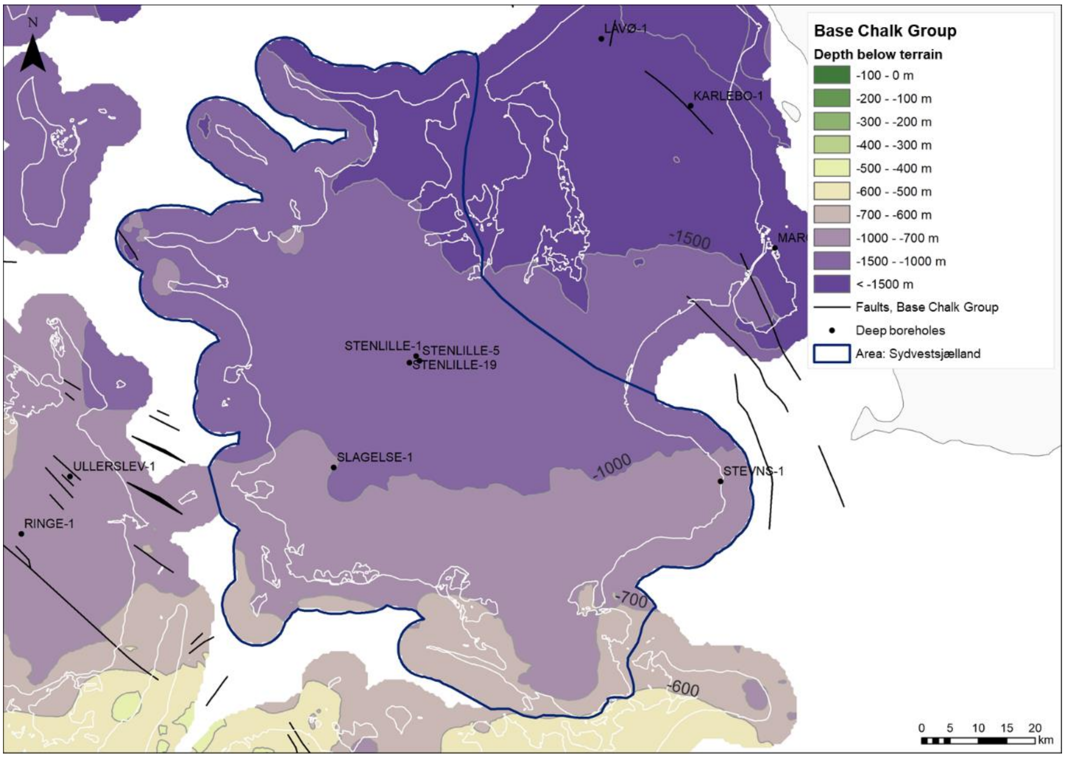


Figure 6.120. *Top Lower Cretaceous (base of the Chalk Group) depth map, Sydvestsjælland area. The depth increases from 700 meters in the south (light purple) to 1500 meters or more in the north (purple). Mapped faults intersecting the base of the Chalk Group are shown.*

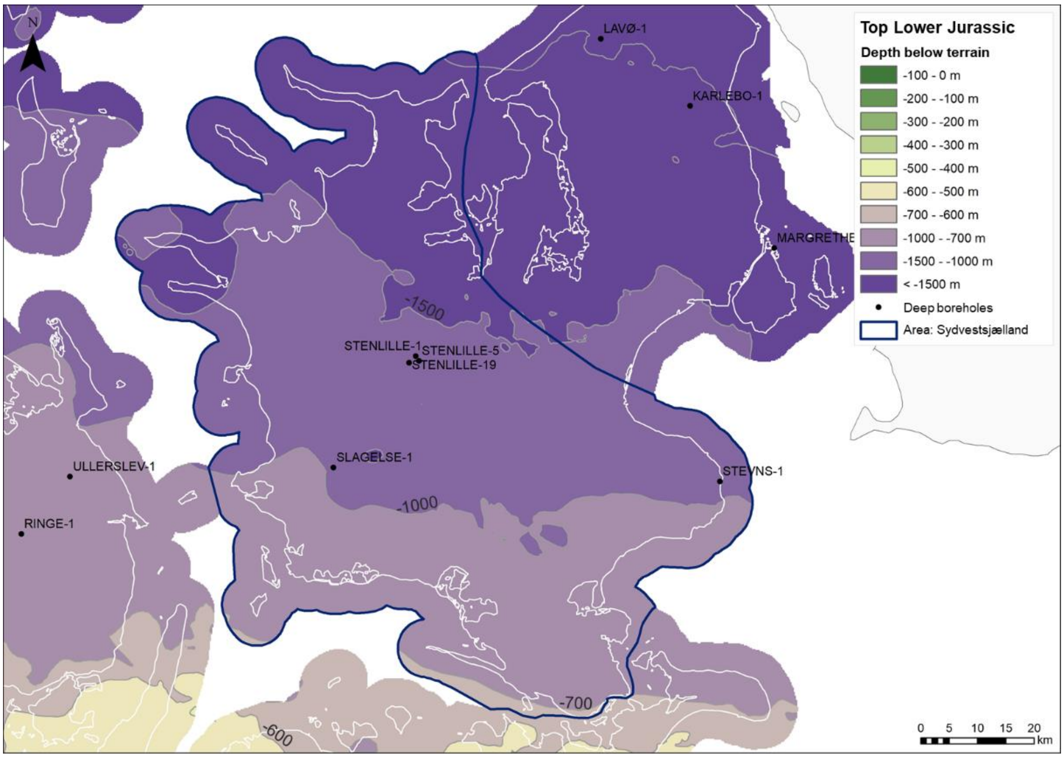


Figure 6.121. *Top Lower Jurassic depth map, Sydvestsjælland area.*

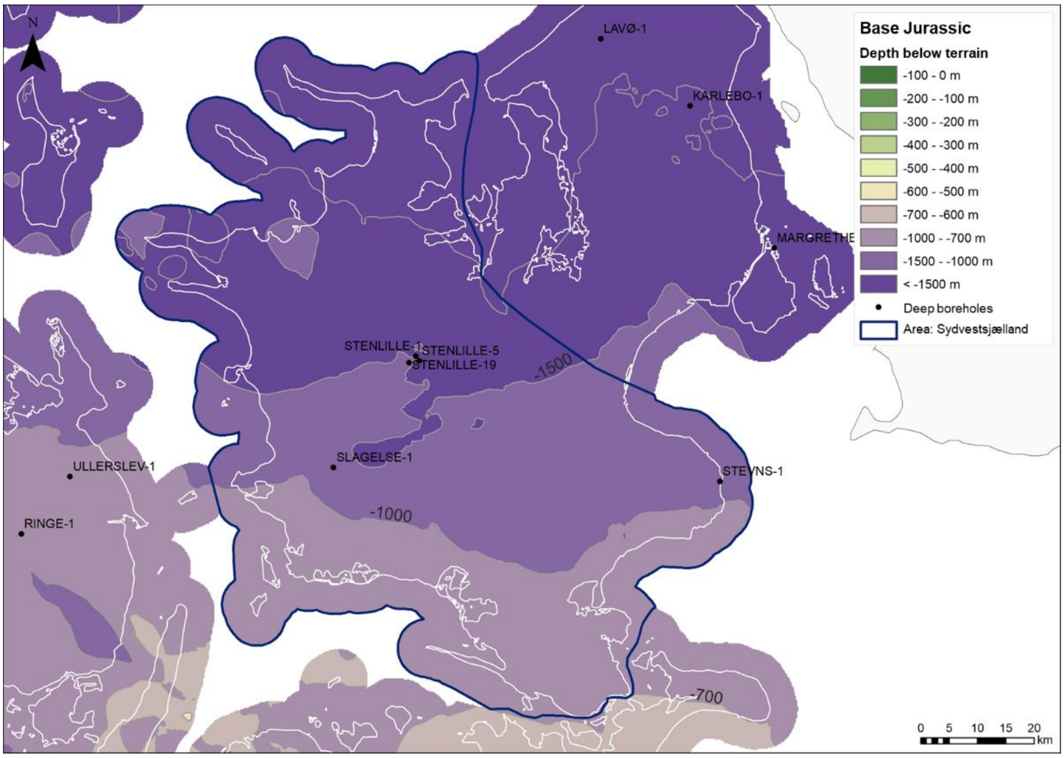


Figure 6.122 *Base Jurassic depth map, Sydvestsjælland area.*

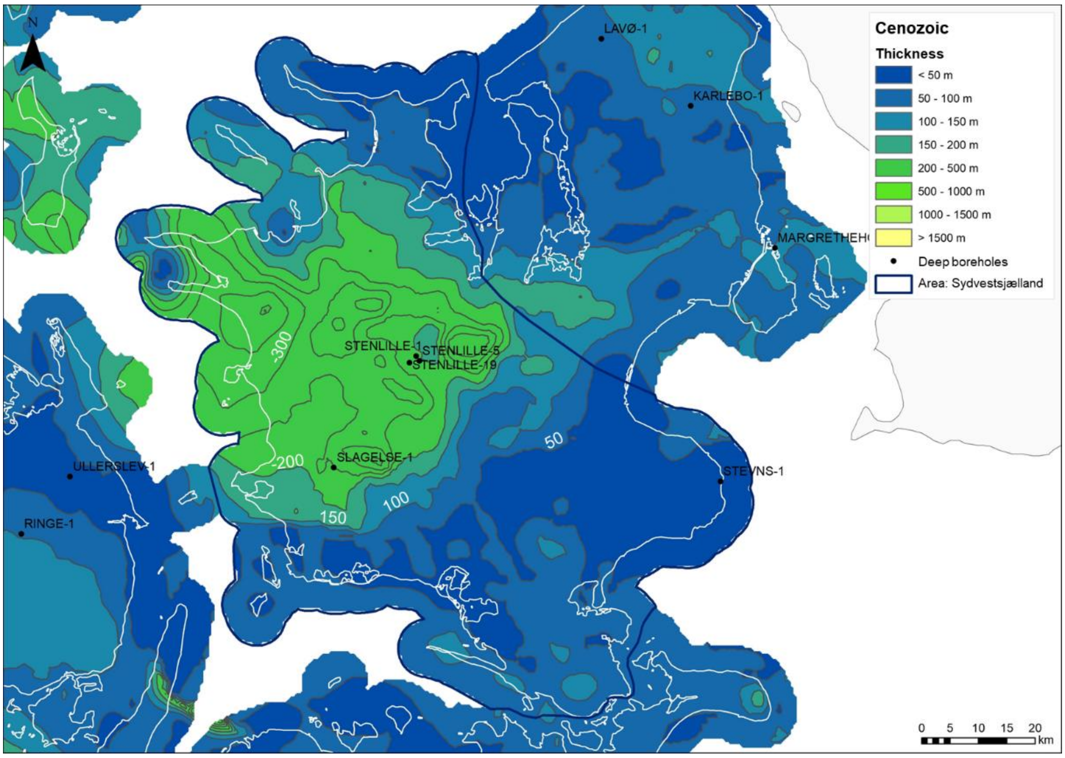


Figure 6.123. *Cenozoic thickness map, Sydvestsjælland area. The map shows that the Cenozoic succession is 0 to 150 meters thick in most of the area. The greatest thicknesses are reached in the western part of the area where they locally exceed 300 meters.*

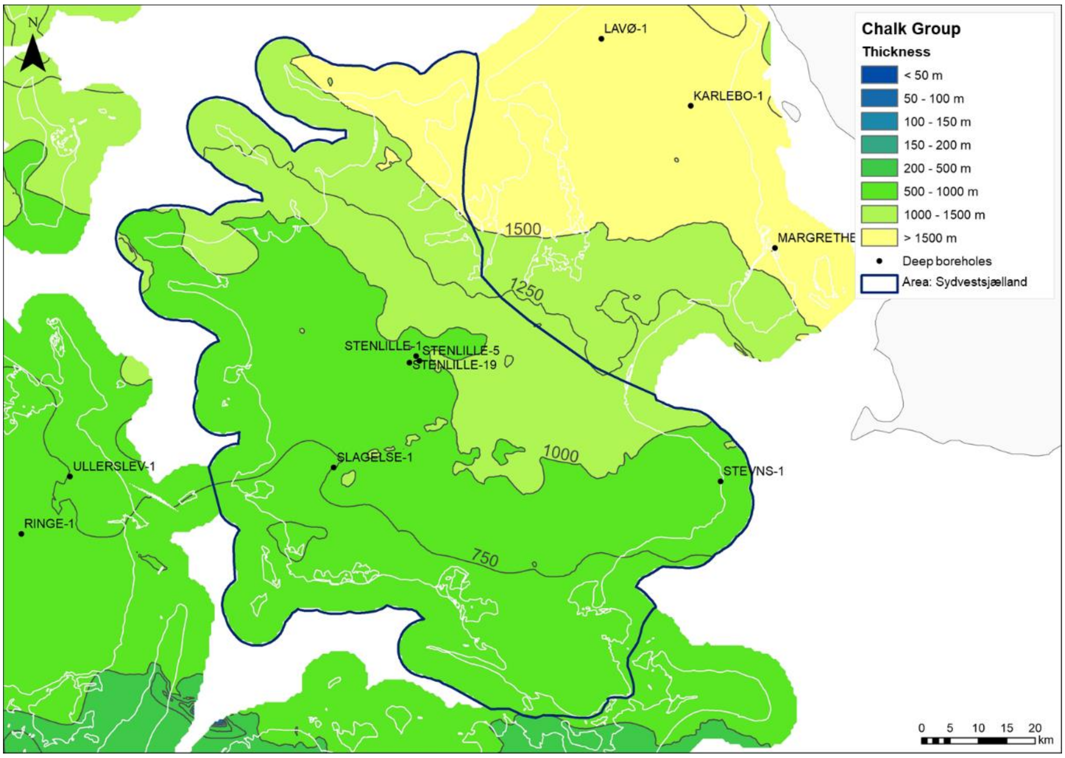


Figure 6.124. *Chalk Group thickness map, Sydvestsjælland area. The map shows that to the south the Chalk Group thickness is approximately 700 meters and increases to more than 1500 meters in the northernmost parts of the area (yellow).*

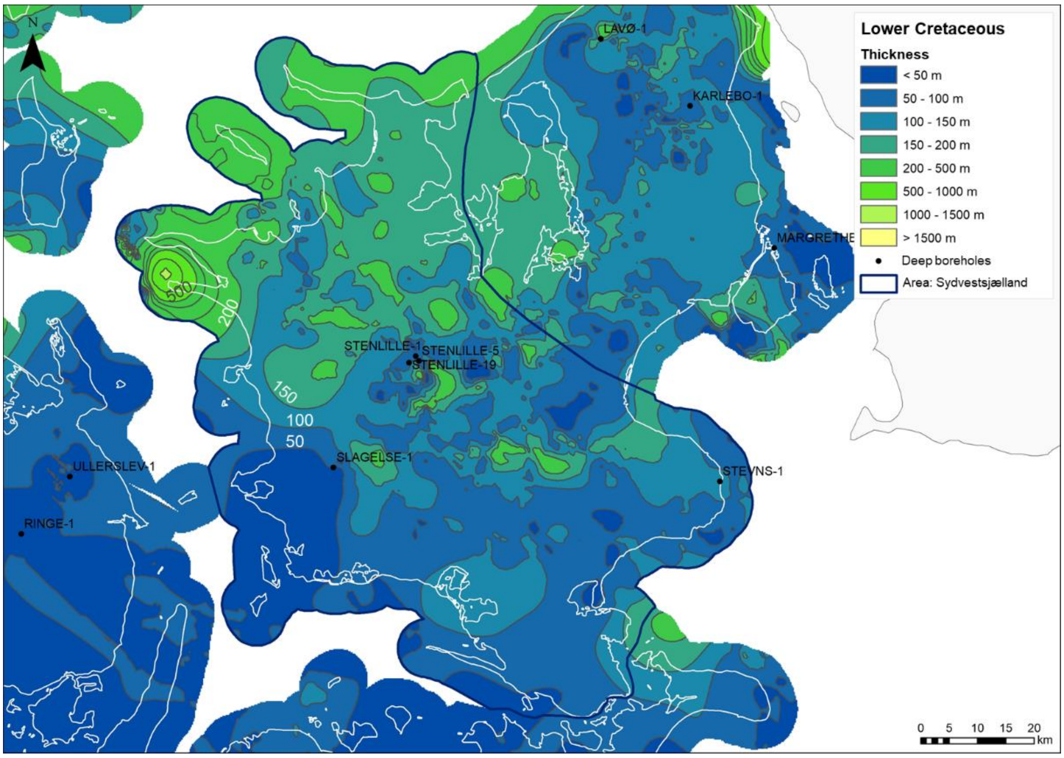


Figure 6.125. *Lower Cretaceous thickness map, Sydvestsjælland area. The map shows that the thickness is generally between 0 and 200 meters.*

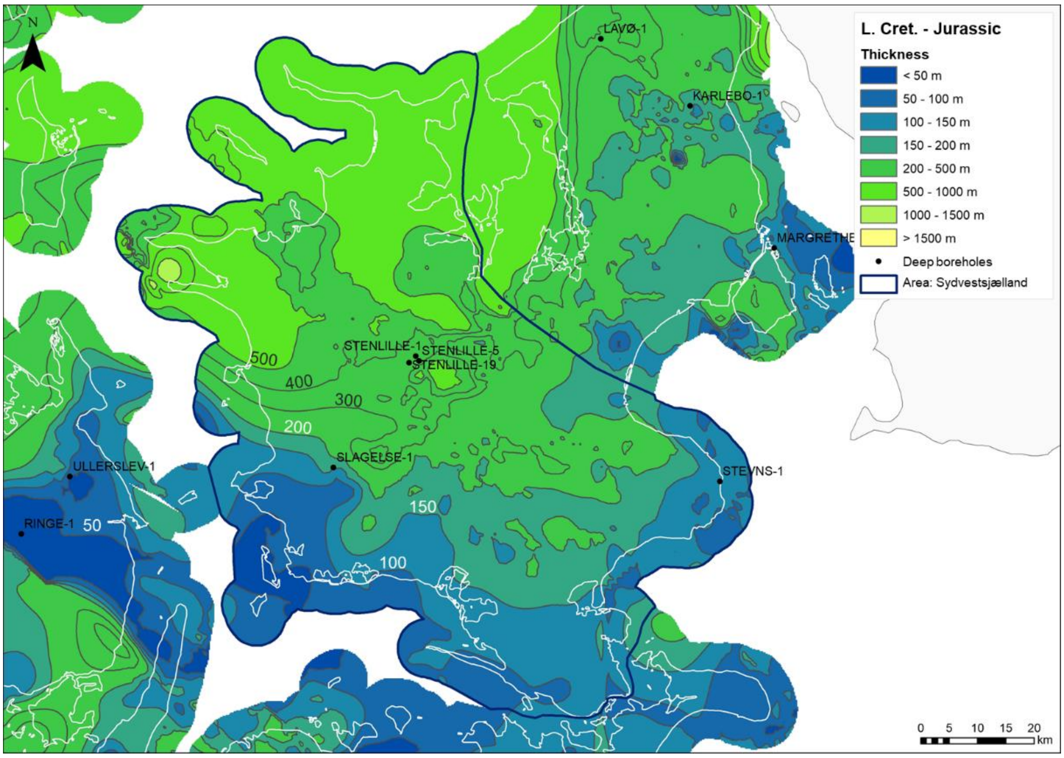


Figure 6.126. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Sydvestsjælland area.*

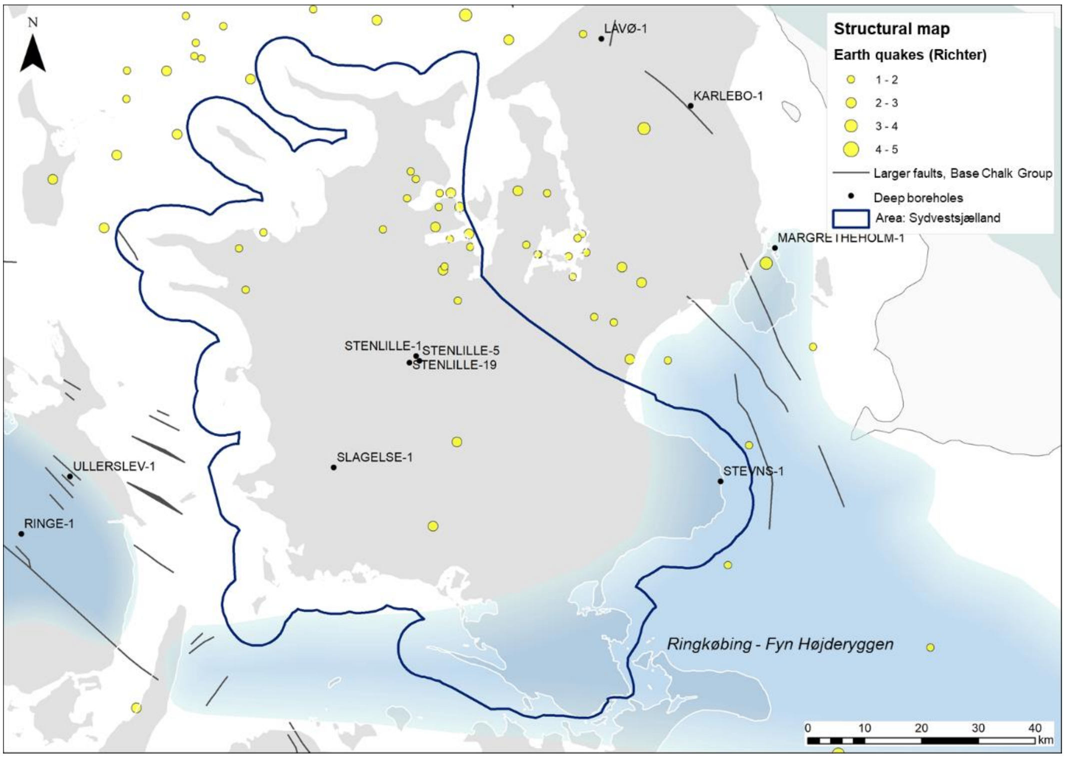


Figure 6.127. *Earthquakes registered during the past 50 years plotted on a structural map, Sydvestsjælland area. Earthquakes have been recorded frequently in the northern part of the area and to the east and north of the area with magnitudes ranging from 1-4 (Richter scale).*

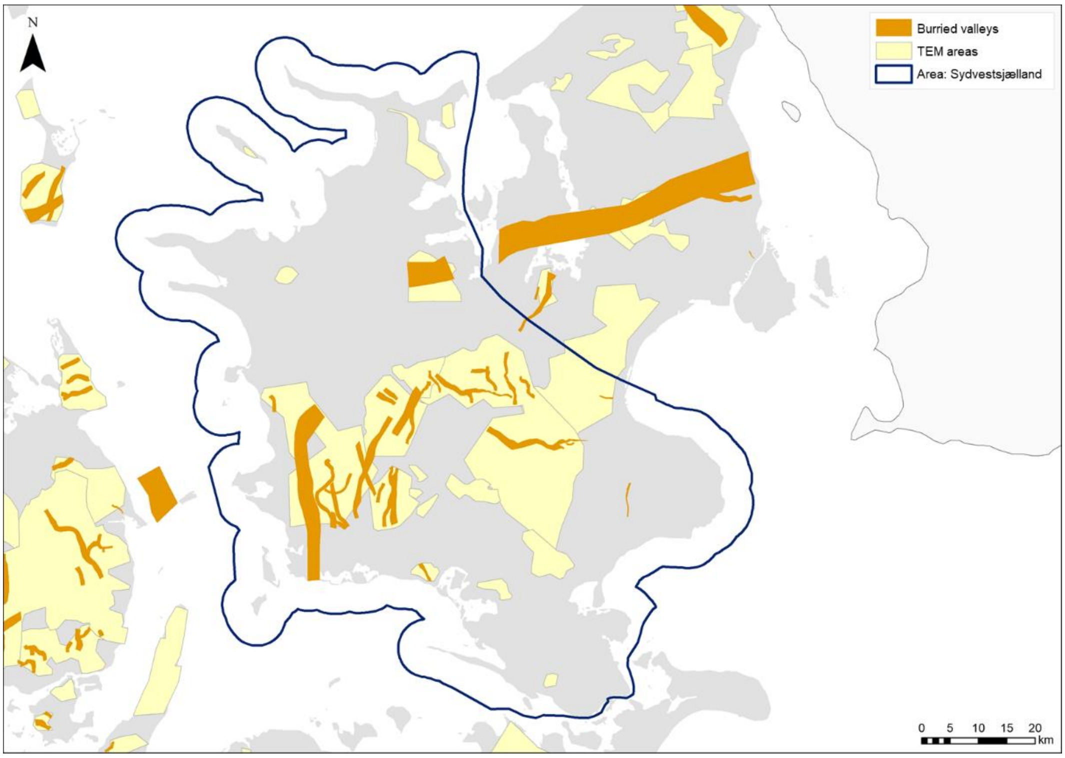


Figure 6.128. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Sydvestsjælland area.*

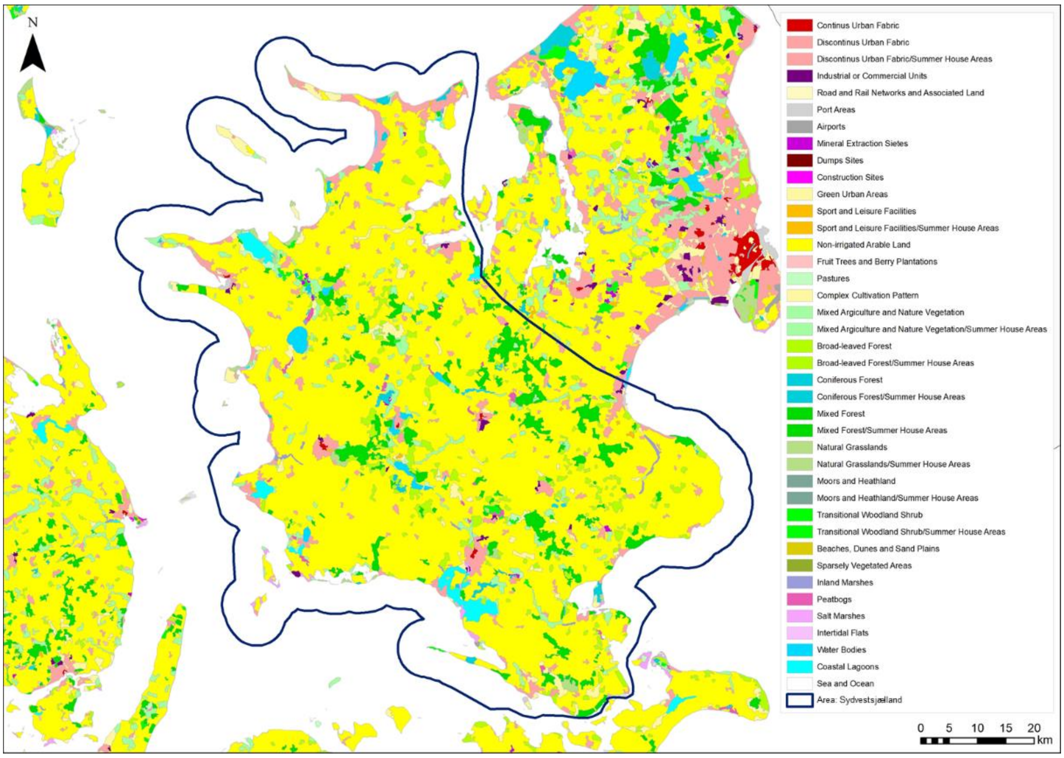


Figure 6.129. *Land use, Sydvestsjælland area (MiljøGIS, 2021).*

6.10 Nordøstsjælland

Carbonates constitute the 400–500 meters depth interval and occur with thicknesses varying from 1200 meters to more than 1500 meters. The top of the Chalk Group occurs at depths around 100 meters and carbonate therefore constitutes a potential host rock as well as a barrier rock in the ECZ (Figures 6.131-6.133 and 6.137). The carbonate succession is horizontally continuous without identified major faults in much of the area (Figures 4.25 and 4.26). However, in the northern and eastern parts several large faults are identified (Figures 6.133 and 6.140), but it is expected that sites without major faults can be identified and confirmed by new seismic data. The natural stability (criterion 2.1) in Nordøstsjælland is scored as less suitable (orange) due to the combination of numerous registered earthquakes and the presence of large, deep seated faults with fault planes extending to near terrain (Figures 6.141 and 4.26). This less favourable situation means that emphasis must be placed on detailed seismic mapping to ensure major faults are absent or at a safe distance in case a site is to be identified in the area.

Table 6.13. *Evaluation of carbonate host rock (Upper Cretaceous Chalk Group), Nordøstsjælland area.*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

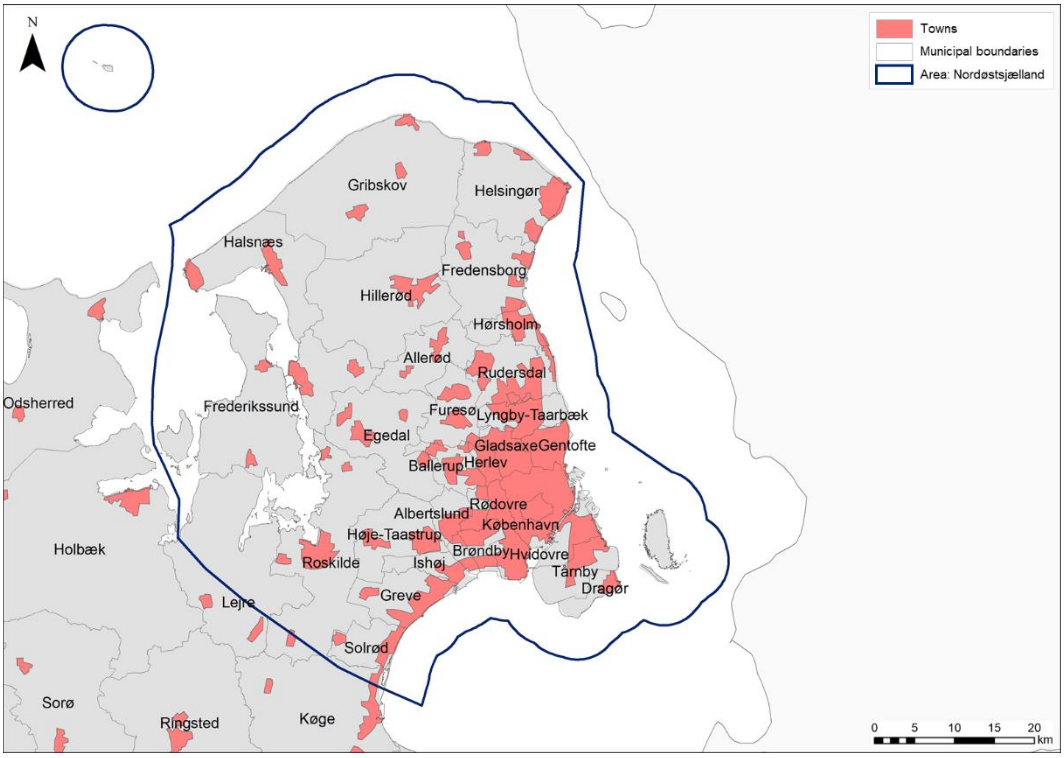


Figure 6.130. *Geographic outline of the Nordøstsjælland area with towns and municipal boundaries indicated.*

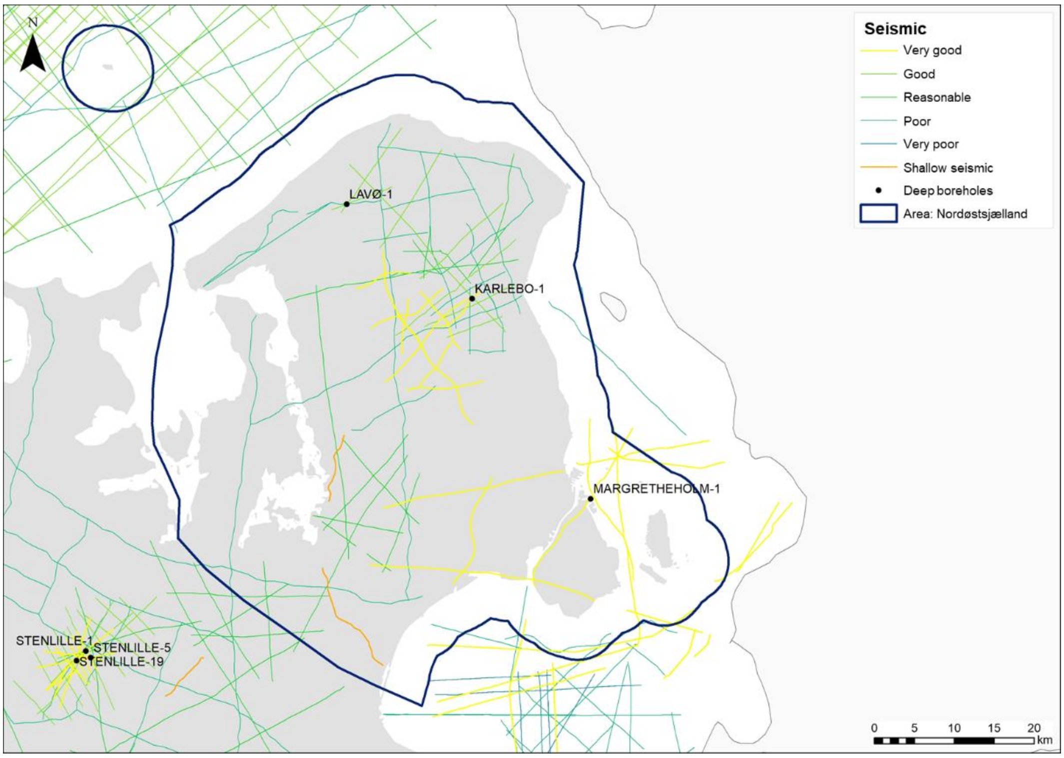


Figure 6.131. *Location map showing seismic lines and their quality, and deep boreholes, Nordøstsjælland area.*

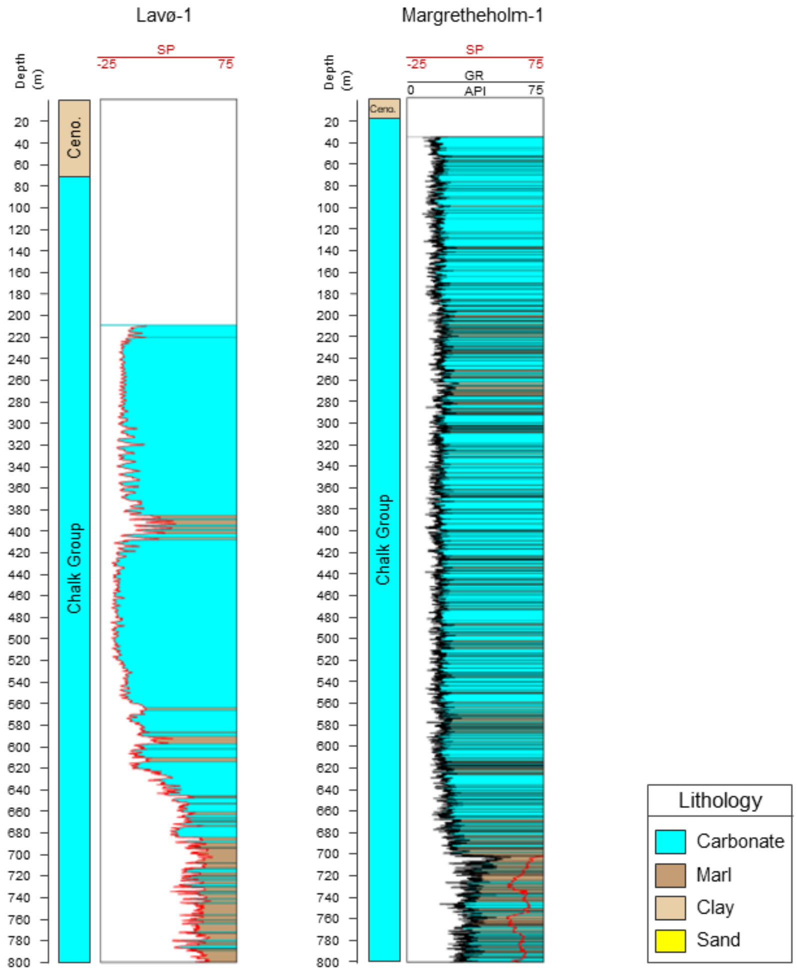


Figure 6.132. *Lithological well log interpretations of the 0–800 meters depth interval from the only two deep boreholes in the Nordøstsjælland area where well logs have been acquired. The figure illustrates that the top of the Chalk Group occurs at shallow depths (70 meters in Lavø-1 and 20 meters in Margretheholm-1) and the carbonate section continues below 800 meters depth. Marl layers of varying thickness occur throughout the carbonate succession.*

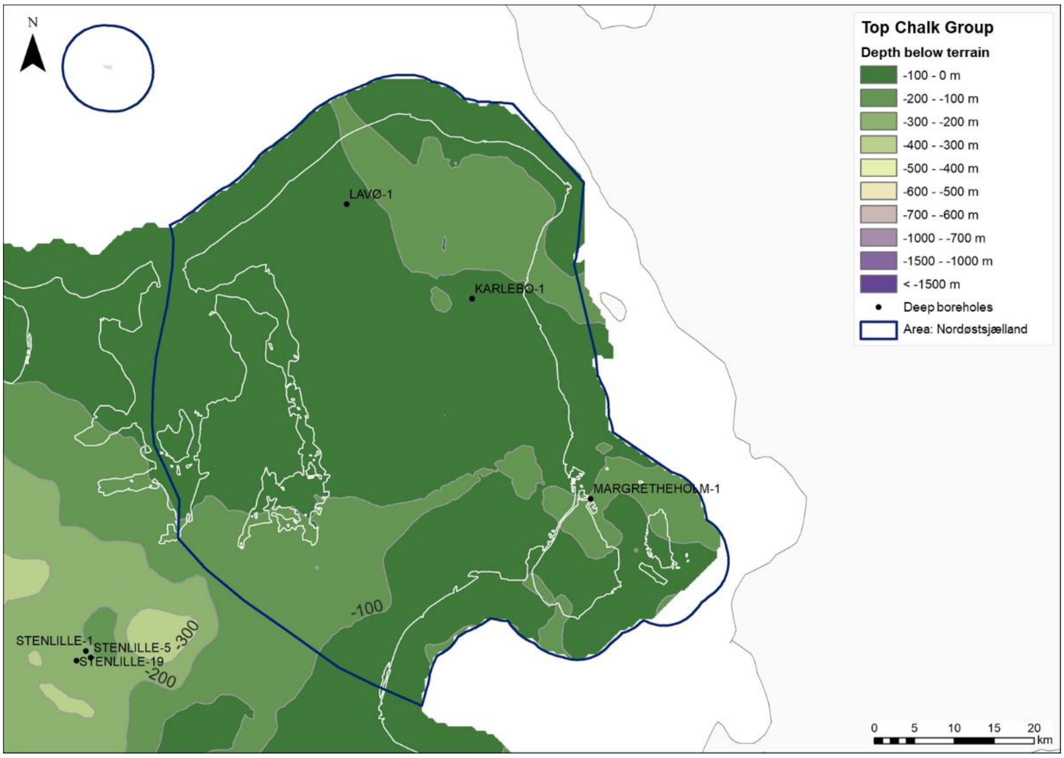


Figure 6.133. *Top Chalk Group depth map, Nordøstsjælland area. The map shows that the top of the Chalk Group generally occurs at depths between 0 and 100 meters.*

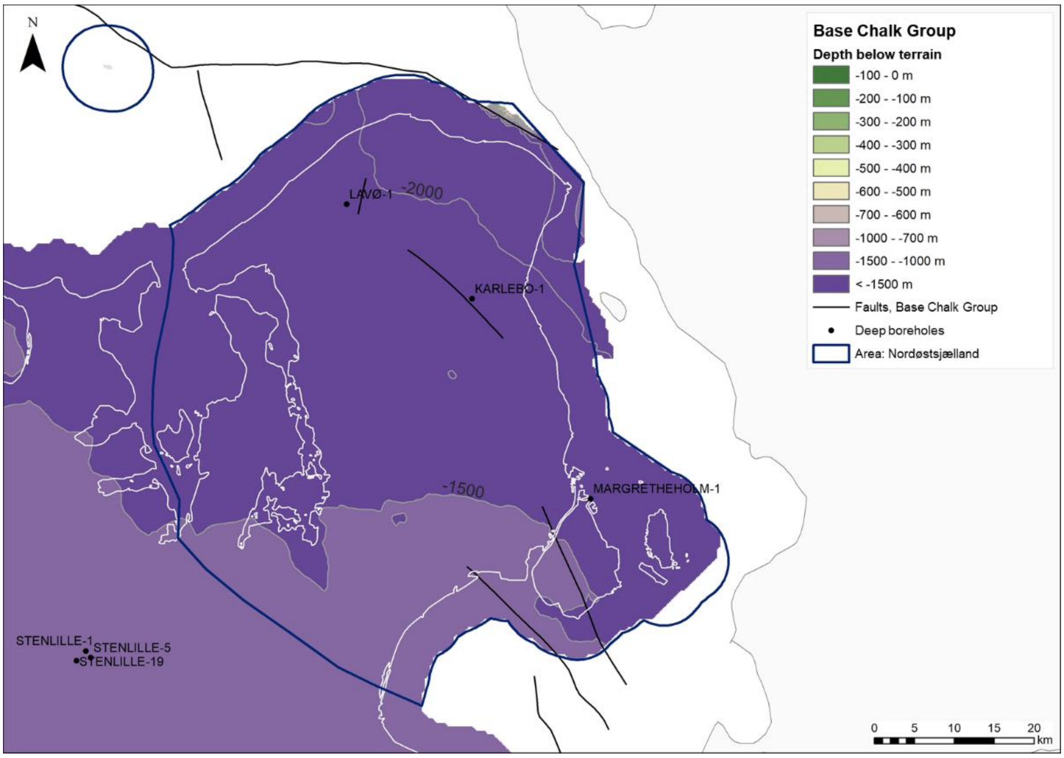


Figure 6.134. *Top Lower Cretaceous (base of the Chalk Group) depth map, Nordøstsjælland area. Mapped faults intersecting the base of the Chalk Group are shown. The map shows that base of the Chalk Group occurs at depths from 1000 meters to more than 2000 meters.*

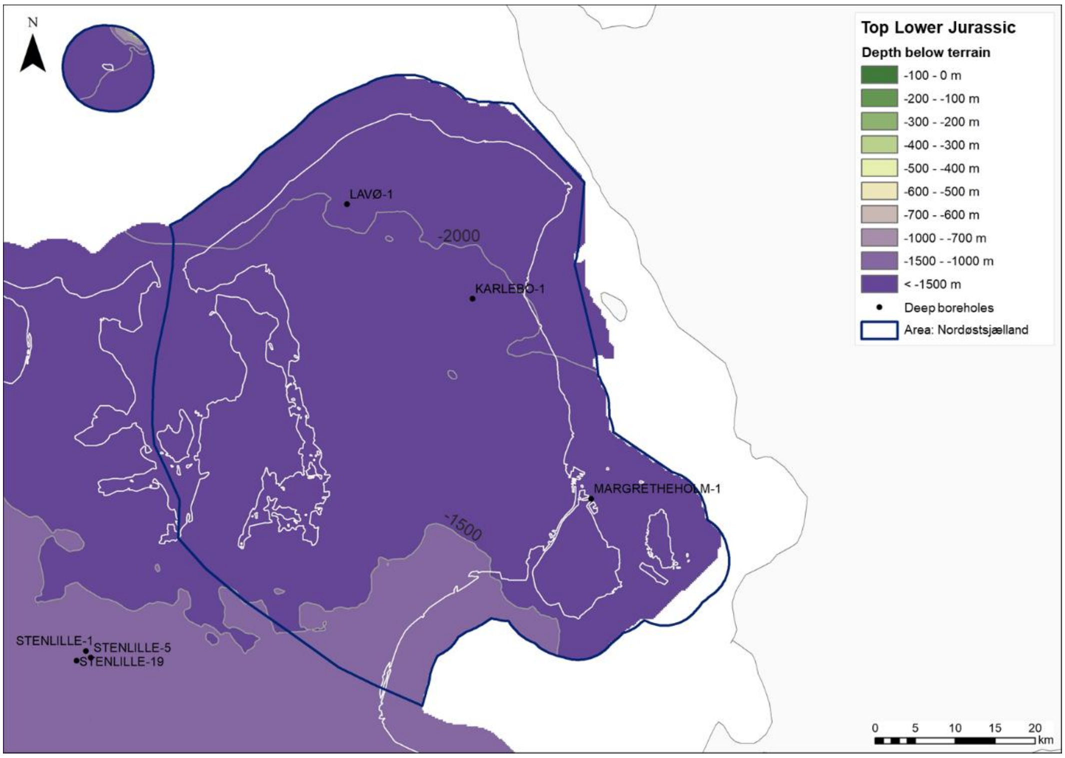


Figure 6.135. *Top Lower Jurassic depth map, Nordøstsjælland area.*

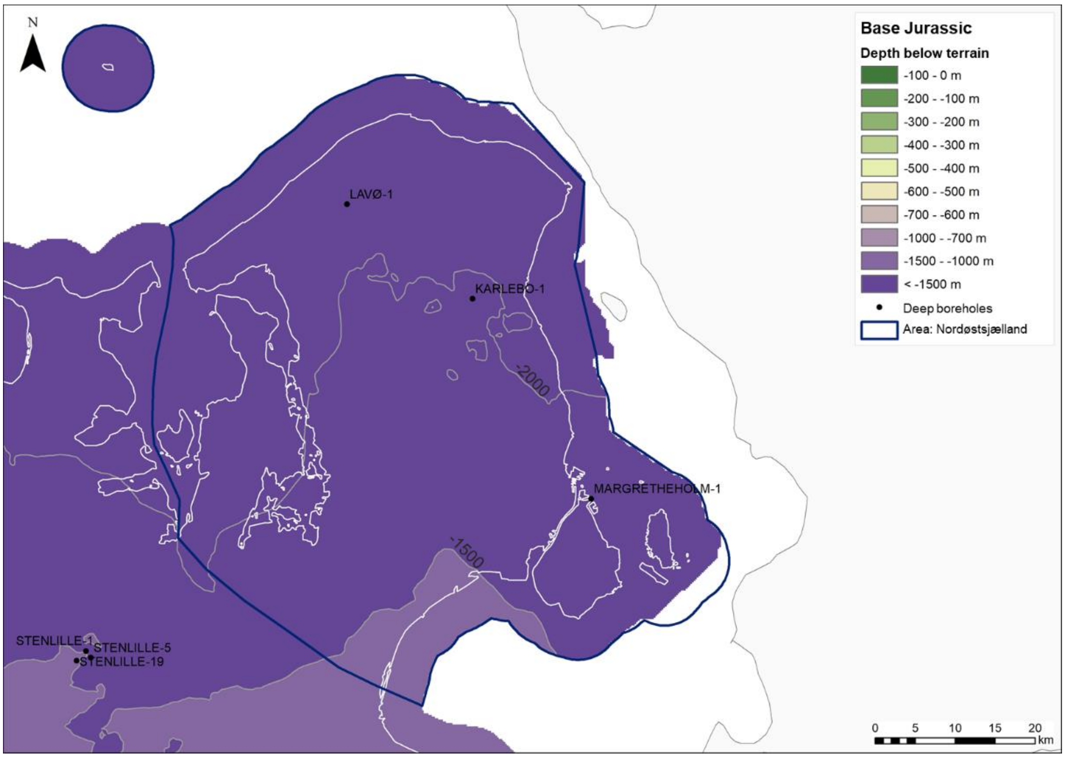


Figure 6.136. *Base Jurassic depth map, Nordøstsjælland area.*

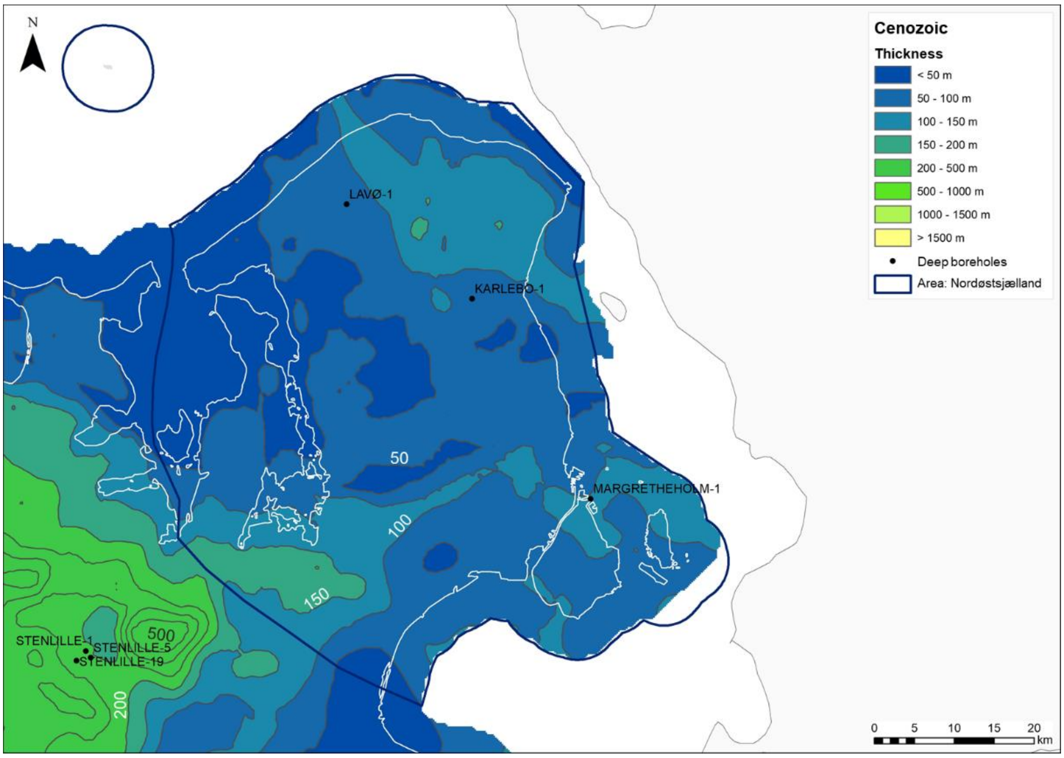


Figure 6.137. *Cenozoic thickness map, Nordøstsjælland area. The map shows that the Cenozoic succession generally has a thickness in the range of 0 to 150 meters.*

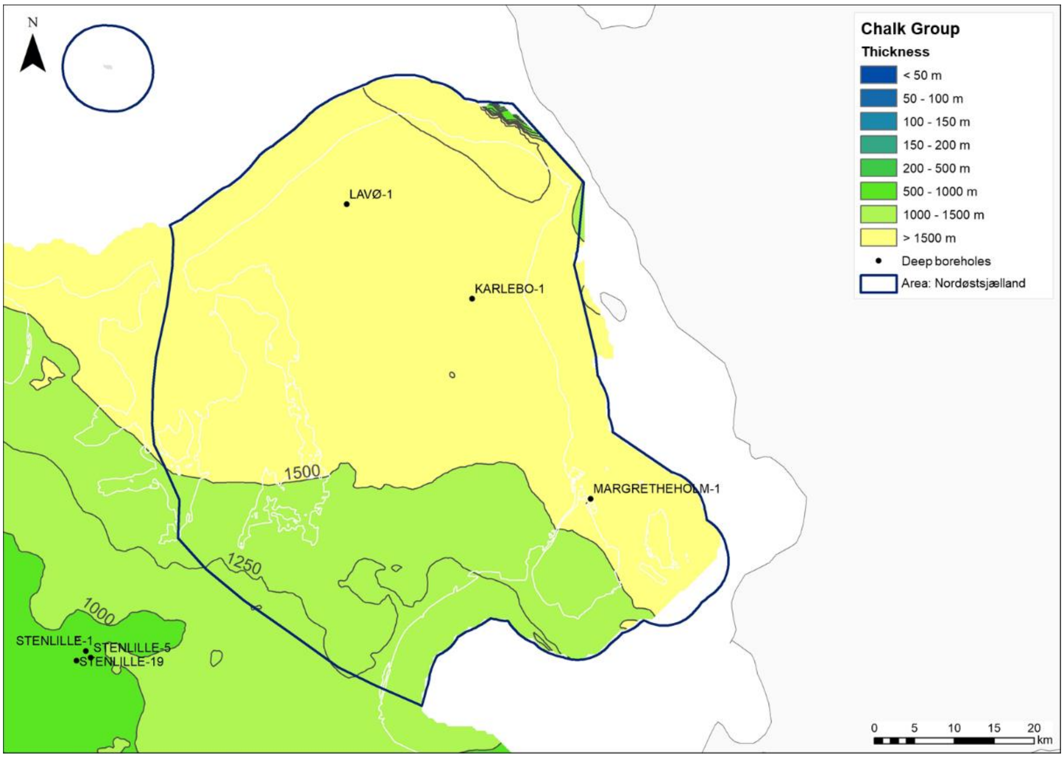


Figure 6.138. *Chalk Group thickness map, Nordøstsjælland area. The map shows that the Chalk Group thickness exceeds 1250 meters.*

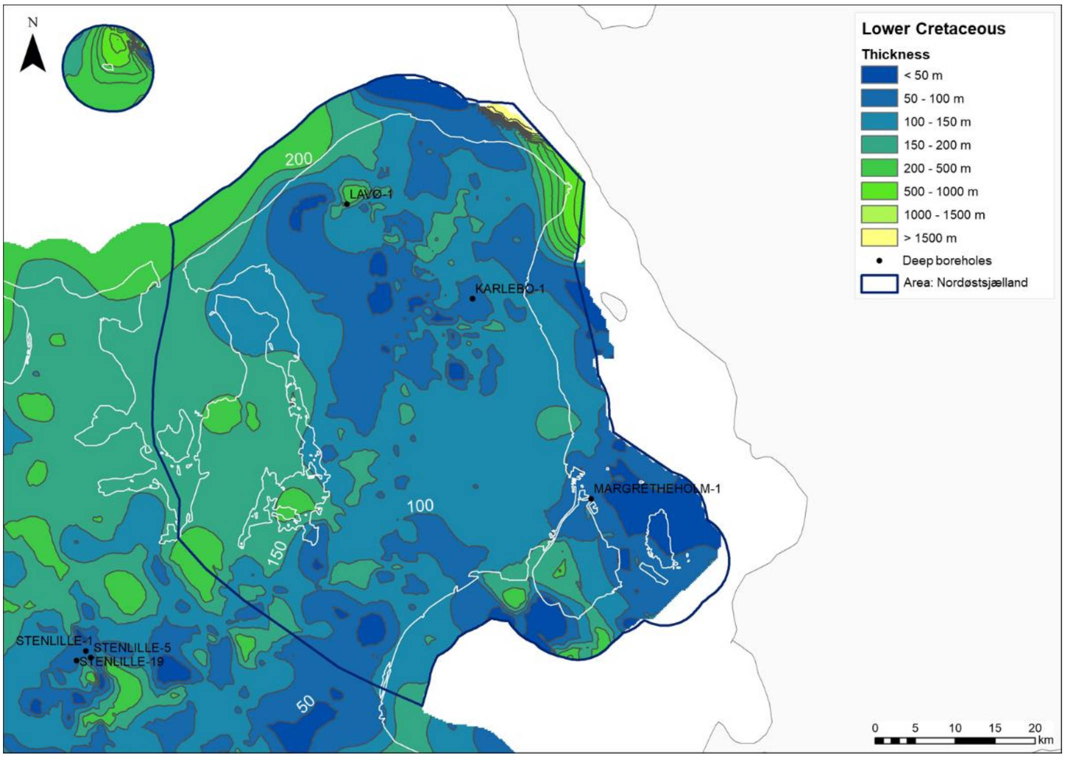


Figure 6.139. *Lower Cretaceous thickness map, Nordøstsjælland area.*

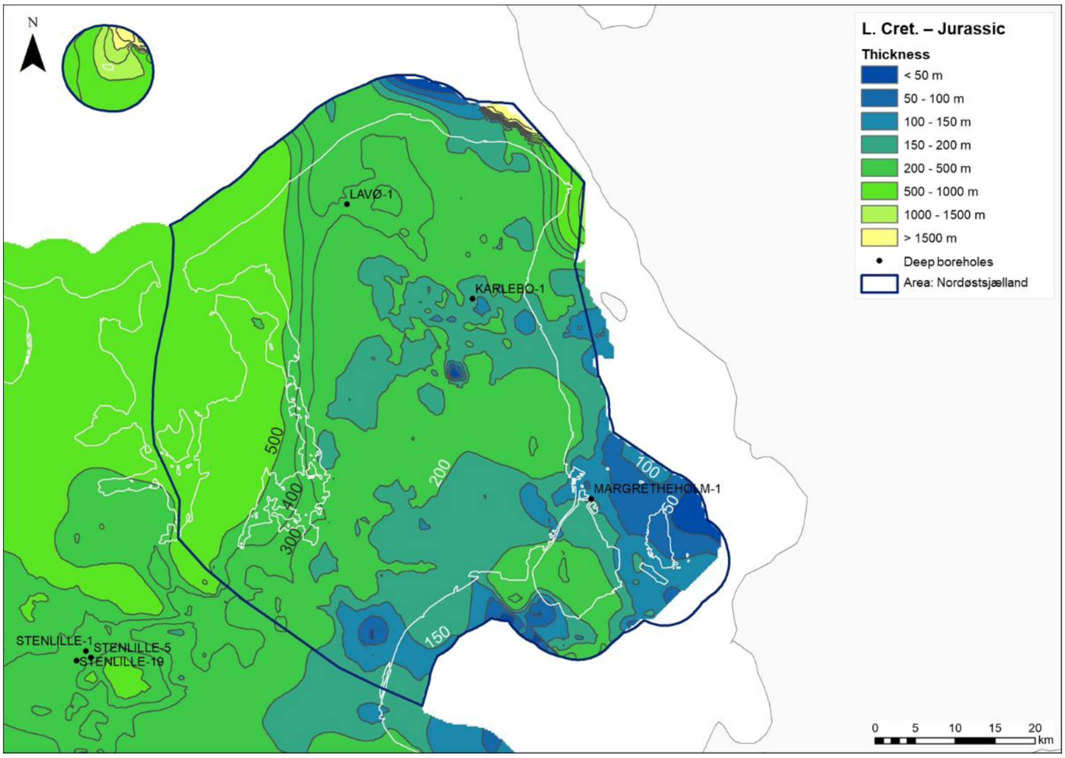


Figure 6.140. *Thickness map of the combined Lower Cretaceous and Jurassic successions, Nordøstsjælland area.*

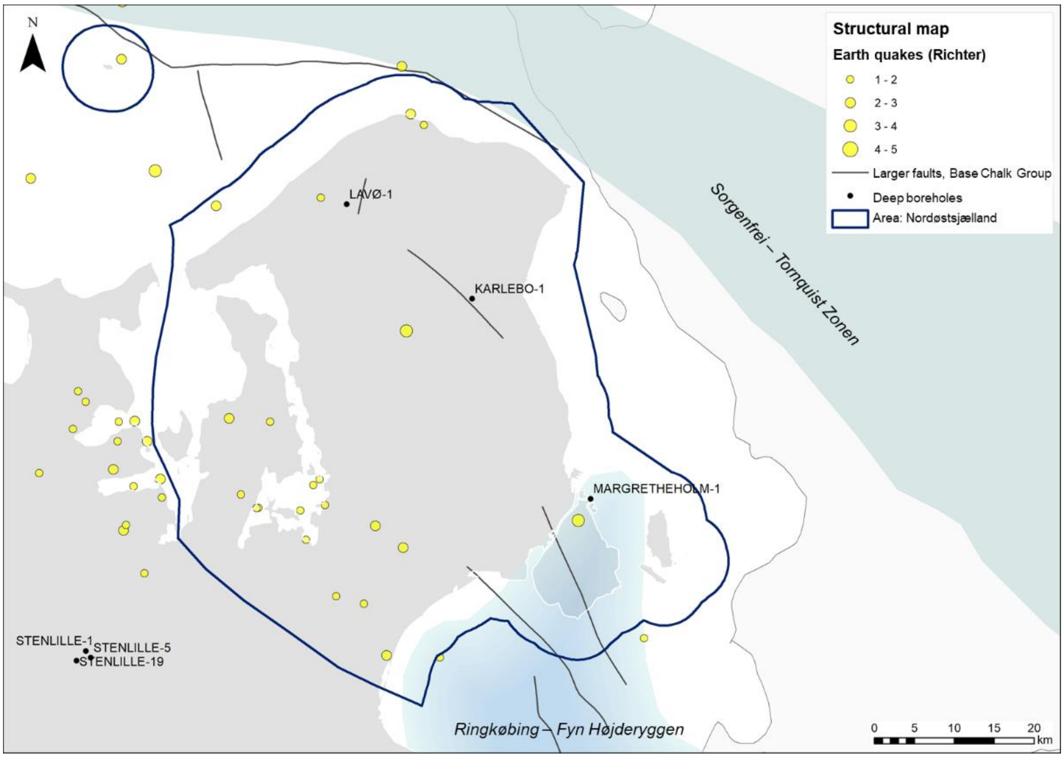


Figure 6.141. *Earthquakes registered during the past 50 years plotted on a structural map, Nordøstsjælland area. Several earthquakes are registered in the area with magnitudes ranging from 1 to 4 (Richter scale).*

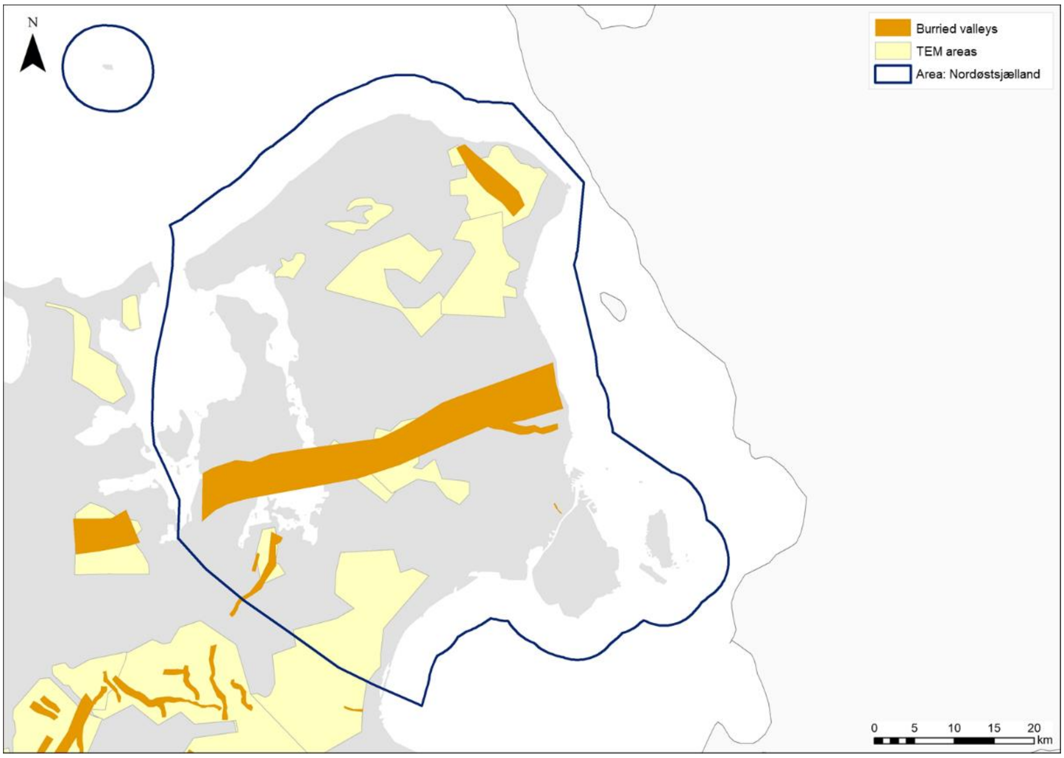


Figure 6.142. *Mapped buried Quaternary valleys (orange) and the coverage of TEM data used for mapping, Nordøstsjælland area.*

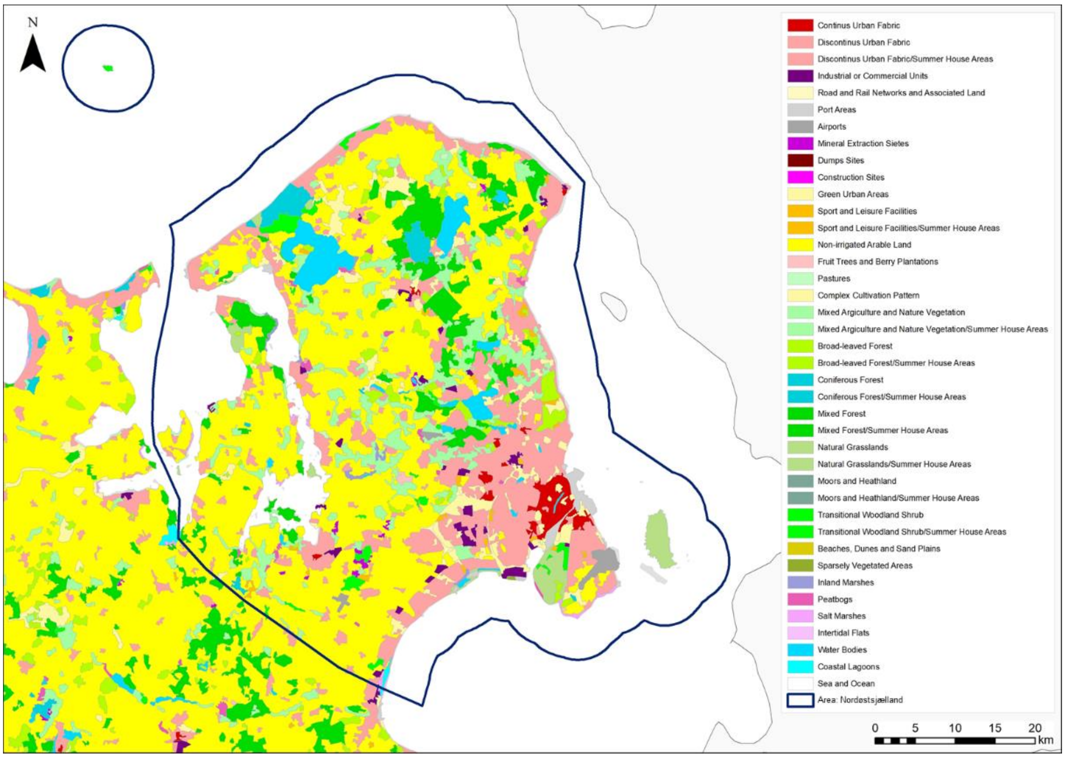


Figure 6.143. *Land use, Nordøstsjælland area. There are relatively large lakes in the northern part of the area (light blue areas) and marine inlets to the west (MiljøGIS, 2021).*

6.11 Bornholm

Crystalline basement of granite and gneiss occurs at shallow depths in the central and northern parts of Bornholm. The crystalline rocks constitute both host rock and barrier rock as the entire interval from near terrain to depths far below 500 meters comprises basement (Figures 4.27 and 4.31).

The basement is horizontally continuous in the area. Locally occurring, large vertical fractures can be mapped at the surface. Numerous smaller fractures are observed extensively at the top of the basement and in natural outcrops and quarries where horizontal fractures are also observed (Figures 4.31 and 6.145).

The geochemical conditions for retardation of radioactive nuclides (Criterion no. 1.3) is scored less suitable because granite, gneiss, and their weathering products do not contain smectite, which is a mineral known to promote retardation of radioactive nuclides. It is possible that the constructed barriers of a potential repository in basement rock can be designed to compensate for the less suitable score of this criterion. This should be investigated further if a site for detailed geological investigations is chosen in the Bornholm basement area.

The host rock's self-healing properties (Criterion 2.3) are scored as less suitable. This is because neither smectite nor calcite has been detected from analysis of rock samples. Both minerals have the capability to precipitate in small, locally generated fractures and self-heal potential repository induced microfractures in the host rock, and thereby ensure the effectiveness of the geological barriers. The criterion for self-healing may not be of importance for crystalline rocks since compaction induced microfractures are less likely to generate in a host rock of crystalline basement compared with a sedimentary host rock. The safety relevance of the self-healing capability of basement rocks may be investigated further, e.g., based on experience from repositories under construction in basement rocks in Sweden and Finland (SKB, 2021; POSIVA, 2021).

Table 6.14. *Evaluation of granite and gneiss host rock (Precambrian), Bornholm area*

Criteria Group	Criteria	Score
1. Properties of the host rock and the containment zone	1.1 Spatial extent	
	1.2 Hydraulic barrier effectiveness	
	1.3 Geochemical conditions for retardation	
	1.4 Release pathways	
2. Long-term natural stability	2.1 Stability of the site and rock properties	
	2.2 Erosion	
	2.3 Repository induced influences	
3. Geotechnical feasibility	3.1 Rock mechanical properties and conditions	
	3.2 Underground access and drainage	
4. Possibility to acquire reliable new geological data	4.1 Ease of characterization of the rock	
	4.2 Explorability of spatial conditions	
	4.3 Predictability of long-term changes	

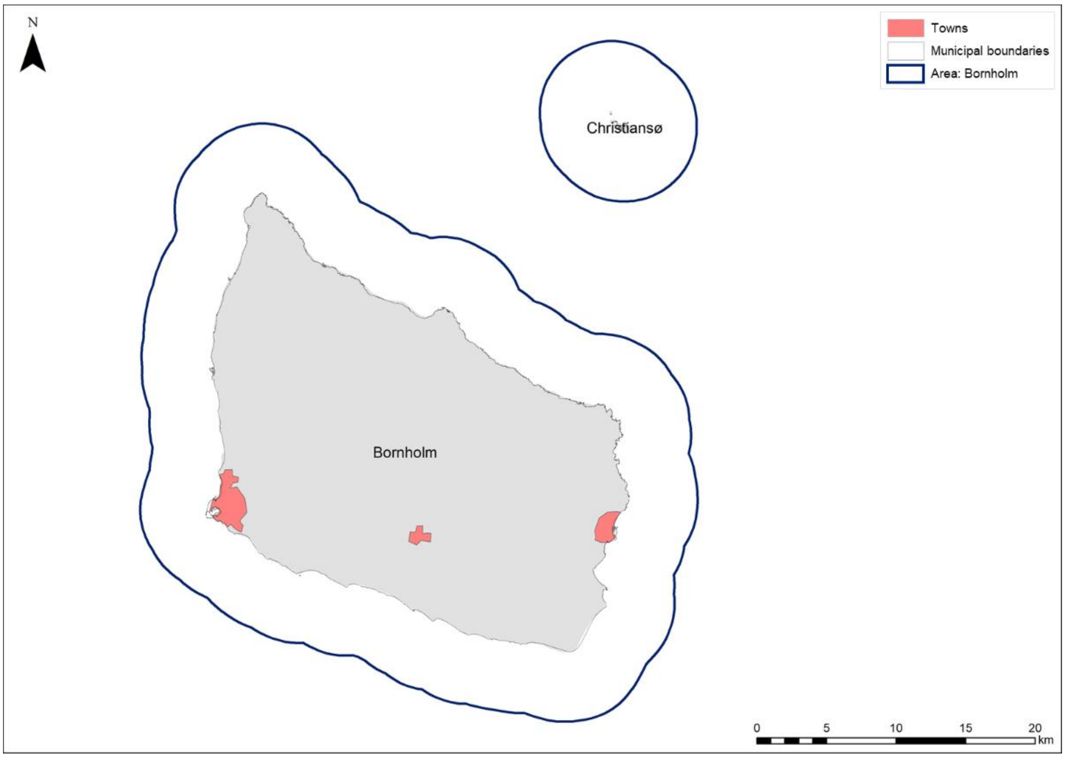


Figure 6.144. *Geographic outline of the Bornholm area and location of towns.*

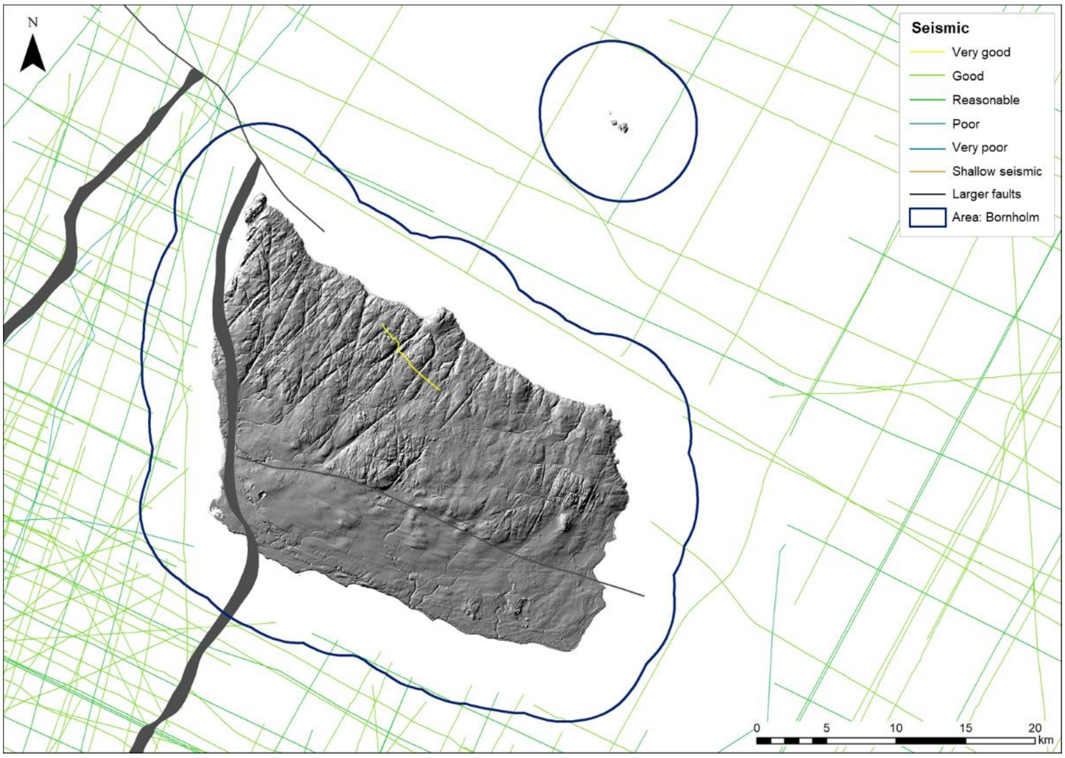


Figure 6.145. *Location map showing seismic lines and their quality, and deep boreholes, Bornholm area, showing that abundant seismic data exist in the adjacent offshore area. The map of Bornholm's surface topography shows the presence of several fracture systems occurring in the basement rocks in the island's central and northern areas.*

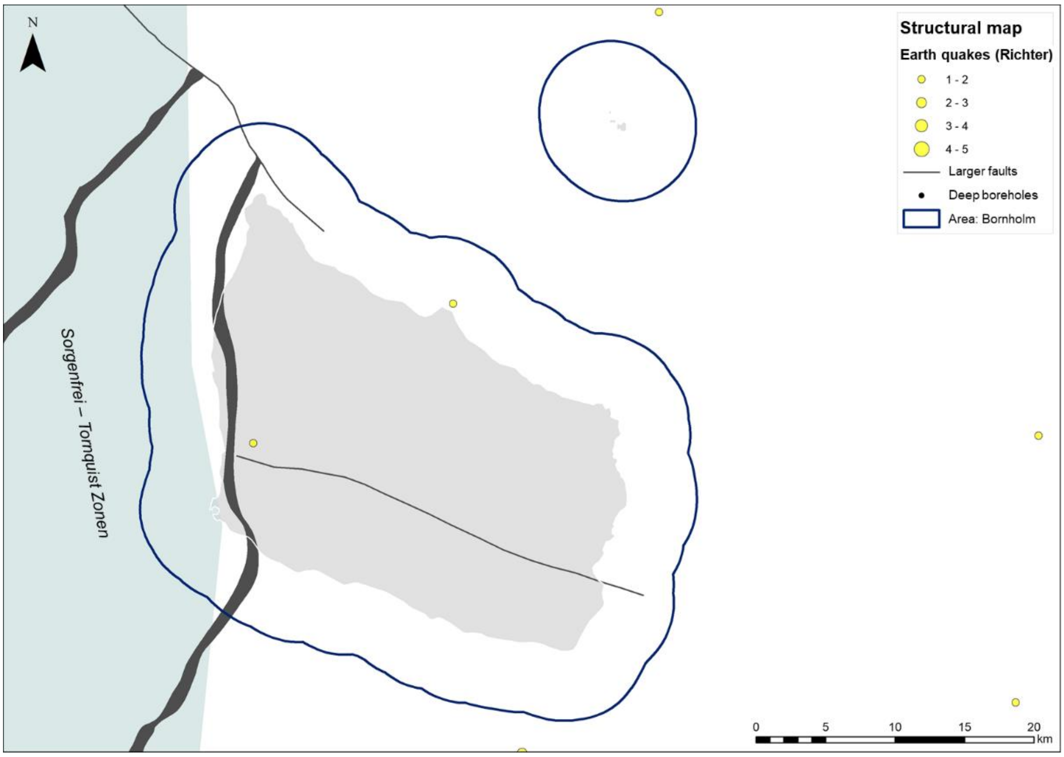


Figure 6.146. *Earthquakes registered during the past 50 years plotted on a structural map, Bornholm area. Only a few small earthquakes with a magnitude of 1-2 (Richter scale) are registered in and adjacent to the Bornholm area.*

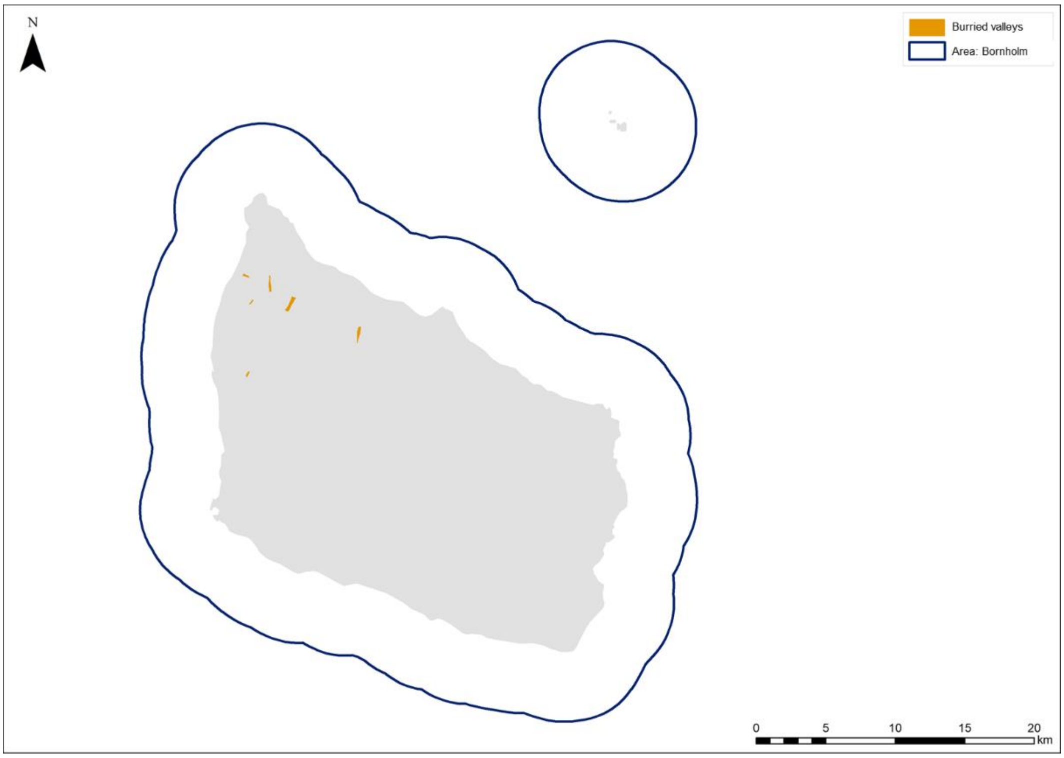


Figure 6.147. *Map of buried Quaternary valleys, Bornholm area. There are no TEM data in this area and the valleys have been mapped from well data.*

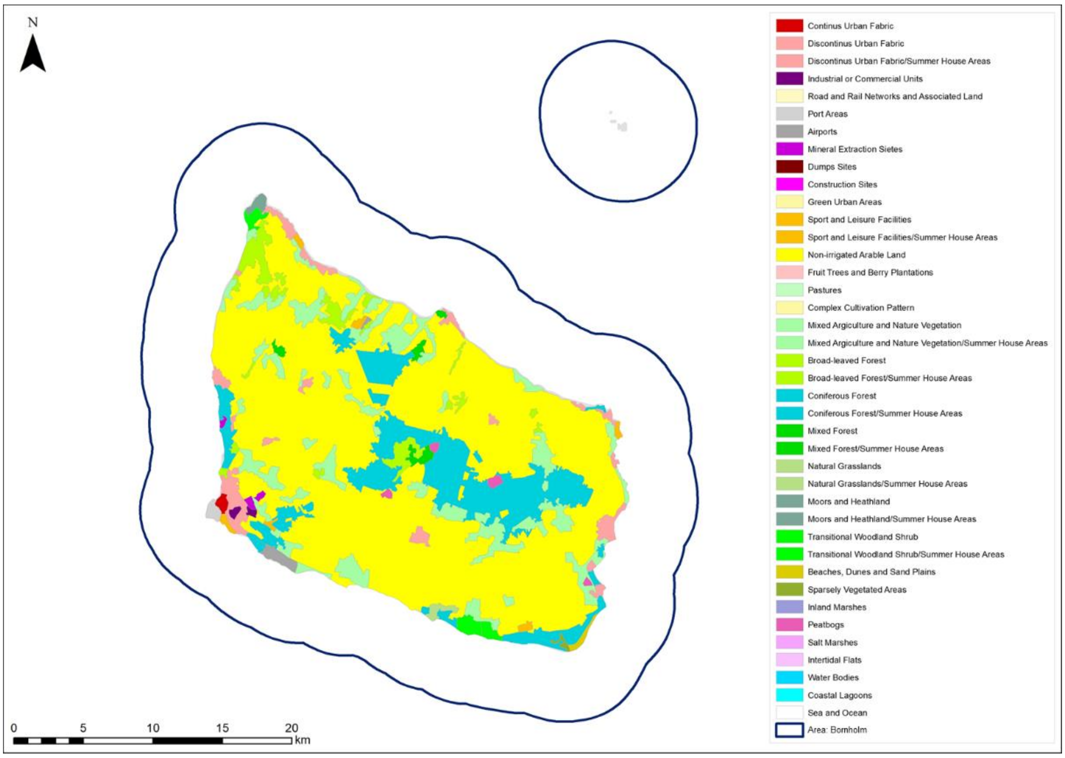


Figure 6.148. *Land use, Bornholm area (MiljøGIS, 2021).*

7. Summary of the area evaluations

The geological properties of the Danish subsurface at depths to 500 meters below ground level have been evaluated in 11 areas (Figure 7.1) based on available data and general geological knowledge. Varying levels of detail exist for the geological properties at 500 meters depth and for some properties data are available only from analogues presented in the literature. Due to the scattered data and the general lack of detailed information, a qualitative assessment of whether the geological criteria are favourable has been carried out for this stage of the siting project.

The area evaluation provides the geological basis for selection of two sites for detailed geological investigations in the project's next phase. An assessment has been carried out based on criteria and related properties and conditions that should ensure safety during construction and operation, and for long-term safety at the site. In the next project phase site-specific data will be acquired with the purpose of evaluating the safety performance of the geological barriers and the natural stability with regards to geological disposal of the radioactive waste at 500 meters depth. The purpose of the geological siting project is to identify areas where the subsurface properties and conditions provide geological barriers ensuring retention and retardation of the radioactive nuclides in the subsurface. The purpose of the project is not to identify "the best site"; this is not possible due to the many different parameters influencing safety, including the disposal concept and the performance of the engineered barriers which have not yet been identified by DD (Dansk Dekommissionering, 2021).

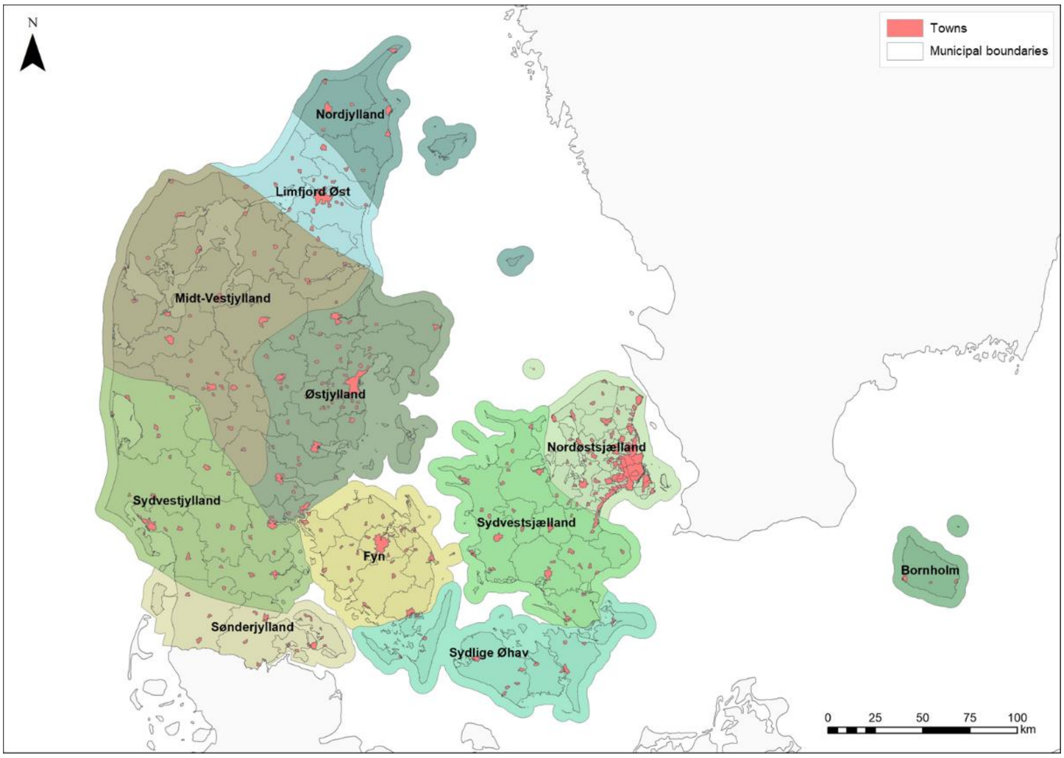


Figure 7.1. *Map showing the outline of the 11 geological areas in this project. Only the onshore areas delineated by the polygons are of interest for disposal.*

An overview of the criteria evaluation of the areas is presented in Table 7.1. The table shows that most geological properties are scored green or yellow indicating they are regarded as suitable or are expected to be suitable for deep geological disposal. The many yellow scores reflect the limited amount of data from depths to 500 meters, i.e. immature databases. In areas where criterion 1.1 is scored green or yellow it is expected that suitable investigation sites where favourable properties are likely to be confirmed, can be identified. Criteria group 3 regarding engineering feasibility is scored yellow in all areas due to the general absence of specific geological data and experience from engineered constructions at 500 meters depth. The green and yellow scorings of criteria in group 4 indicate that sites where acquisition of new representative and reliable data is feasible can be identified in all areas. However, in areas with yellow scorings further data and studies might be needed to identify suitable investigation sites. The new data will enable a detailed characterization and evaluation of the site-specific properties and conditions, and their safety performance.

Table 7.1 *Overview of the criteria scoring for each evaluated area and host rock. A short explanation of the rationale for each of the orange scorings is presented in the report text with reference to the numbers shown in the table.*

	Nordjylland	Nordjylland	Limfjord Øst	Limfjord Øst	Midt-Vestjylland	Østjylland	Sydvestjylland	Sønderjylland	Fyn	Sydlige Øhav	Sydlige Øhav	Sydvestsjælland	Nordøstsjælland	Bornholm
Criteria	Carb.	Clay	Carb.	Clay	Carb.	Carb.	Carb.	Carb.	Carb.	Carb.	Clay	Carb.	Carb.	Granite
1.1 Spatial extent	Orange 1)	Orange 2)	Yellow	Orange 4)	Orange 6)	Green	Orange 8)	Orange 9)	Green	Yellow	Orange 10)	Green	Green	Green
1.2 Hydraulic barrier effectiveness	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green
1.3 Geochemical conditions for retardation	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Orange 13)
1.4 Release flow paths	Yellow	Orange 3)	Yellow	Orange 5)	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Orange 11)	Yellow	Yellow	Yellow
2.1 Stability of the site and rock properties	Yellow	Yellow	Yellow	Yellow	Orange 7)	Yellow	Green	Green	Green	Yellow	Yellow	Yellow	Orange 12)	Green
2.2 Erosion	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green	Green	Yellow	Yellow	Green
2.3 Repository induced influences	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Orange 14)
3.1 Rock mechanical properties and conditions	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
3.2 Underground access and drainage	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
4.1 Ease of characterization of the rock	Yellow	Yellow	Green	Green	Yellow	Green	Green	Green	Green	Green	Green	Green	Green	Green
4.2 Explorability of spatial conditions	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
4.3 Predictability of long-term changes	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green

7.1 Comments to the criteria scored as less suitable (orange)

Table 7.1 shows that in some areas one or more criteria are scored as less suitable indicating that the geological properties and conditions generally do not fulfill the defined criteria. A short explanation of the reason for the less suitable scoring of each of the 14 criteria with an orange score is presented below. The terminology used for the geological concept with a host rock for disposal and overlying barriers in the ECZ is illustrated in Figures 2.3 and 5.1.

1. In the Nordjylland area the carbonate section in the ECZ is generally 0 to 200 meters thick. Therefore, the criterion regarding the presence of a 250 meters thick section of tight rock in the ECZ in combination with a 100 meters thick host rock section at the depth around 500 meters is not fulfilled and criterion 1.1 is scored less suitable. However, locally in the southernmost part of the area carbonates may constitute a 250

meters thick section in the ECZ and thus provide the required thickness of tight rock overlying the host rock interval.

2. In the Nordjylland area the presence of a host rock section of 100 meters of homogeneous claystone has not been proven, as the claystone succession comprises numerous meters thick sand layers. Thus, the criterion regarding the presence of a 100 meters thick homogeneous host rock is not fulfilled. Further, successions of carbonate in the ECZ vary in thickness from 0 to 200 meters and do not fulfill the criterion regarding 250 meters of tight rock. Criterion 1.1 regarding the spatial extent of host rock and barriers in the ECZ is not fulfilled in the area, and therefore is scored as being less suitable.

3. In the Nordjylland area sand layers occur in the potential claystone host rock section and in the underlying successions immediately below 500 meters depth in the Jurassic and Lower Cretaceous sections. These sand layers may act as flow paths and criterion 1.4 is therefore scored as less suitable.

4. In the Limfjord Øst area a 100 meters thick section of claystone host rock has not been proven to occur with a thickness of 100 meters in the host rock interval. Furthermore, the Lower Cretaceous claystone succession comprises numerous sand layers. The criterion for a host rock to be at least 100 meters thick and lithologically homogeneous is therefore not fulfilled and the criterion is scored as less suitable. Additionally, the horizontal continuity of both claystone host rock and carbonates in the ECZ is limited due to the presence of numerous faults offsetting the layers which results in a less suitable score, also for the spatial distribution requirement of criterion 1.1.

5. In the Limfjord Øst area the potential claystone host rock section comprises numerous sand layers which may act as flow paths both in the Lower Cretaceous section and the underlying Jurassic section. Criterion 1.4, stating that flow paths are absent is therefore not fulfilled and is scored as less suitable.

6. In the Midt-Vestjylland area the carbonate succession in the EZC is 200 meters thick, or less, and therefore does not fulfill criterion 1.1 regarding the presence of 250 meters of tight rocks in the ECZ. The top of the Chalk Group occurs at depths from 300 to 500 meters and the total thickness of the carbonate succession is 500–1000 meters. If disposal is decided upon at depths greater than 500 meters the required thickness of both host rock and barrier in the ECZ may be obtained.

7. In the Midt-Vestjylland area numerous salt structures which may still be active or can be reactivated and thereby cause offset along fault planes, are present. Several earthquakes have been registered, especially in offshore areas to the west, indicating that some faults are active. Due to the presence of salt structures and several registered earthquakes in the area criterion 2.1 regarding the natural stability is scored as being generally less suitable. It may be possible to identify local areas without active faults where the risk of earthquakes is small, and the natural stability may be suitable. Further, new detailed seismic data and mapping in the area is required to identify a suitable investigation site where faults are absent.

8. In the Sydvestjylland area the thickness of carbonates in the ECZ varies from 0 to 200 meters and thus the criterion 1.1 regarding the presence of 250 meters of tight rock is not fulfilled. The top of the Chalk Group occurs at depths from 300 to 500 meters and the total carbonate thickness is 500–1000 meters. In case at depths greater than 500 meters is an option the required thickness of both host rock and barrier in the ECZ may be obtained.

9. In the Sønderjylland area the thickness of carbonates in the ECZ varies between 0 and 200 meters and thus the criterion 1.1 regarding the presence of 250 meters of tight rock is not fulfilled. The horizontal continuity of host and barrier rocks is limited due to the presence of numerous faults associated with vertical off-set of the sections. Therefore criterion 1.1 is not fulfilled due to lack of horizontal continuity.

10. In the Sydlige Øhav area the presence of a homogeneous claystone section with a thickness of 100 meters has not been proven. Lower Cretaceous and Jurassic claystones comprise numerous layers of silt and sand. The potential claystone host rock is therefore not lithologically homogeneous, neither vertically nor laterally and criterion 1.1 is scored as less suitable.

11. In the Sydlige Øhav area the Lower Cretaceous and Jurassic claystone successions constituting a potential host rock comprise numerous sand layers that may act as flow paths. Thick sandstone beds from the Gassum Formation are present in the section immediately below 500 meters depth. Criterion 1.4 is scored as less suitable due to the high amounts of sand in the Gassum Formation which may act as flow paths immediately below the host rock at depths around 500 meters. Furthermore, there is a gradual transition from sand to the overlying clay dominated Jurassic succession and seismic identification and mapping of the Top Gassum Formation is somewhat uncertain.

12. In the Nordøstsjælland area criterion 2.1 regarding natural stability is scored as less suitable due to the frequent occurrence of earthquakes in combination with the presence of numerous fault planes observed to extend to near-surface positions. If these faults are reactivated the fault planes may act as (temporary) flow paths through the tight geological barriers. If investigation sites are selected in this area special emphasis should be placed on ensuring a safe distance to potentially active faults. If a decision is made to dispose the radioactive waste in the area, emphasis should be put on investigations of how the potential impact of earthquakes can be mitigated by the rock's potential for self-healing and by the repository's engineered barriers.

13. In the Bornholm area criterion 1.3 addressing the geochemical properties for retardation of nuclides is scored as less suitable, because the crystalline rocks, granite and gneiss, do not contain smectite clay minerals. However, the matrix permeability of fresh, unweathered crystalline rock is extremely low and the rocks' capability for retardation of nuclides is probably of less importance for the overall barrier effectiveness for a repository compared with a sedimentary host rock.

14. In the Bornholm area the self-healing potential as addressed by criterion 2.3 is scored as less suitable. This is because the crystalline rocks and their weathering products do not comprise smectite or calcite minerals which have the capability to fill locally generated microfractures that may form in the repository due to compaction. However, compaction generated fractures are not expected to form in crystalline rocks, and this criterion may be regarded as less relevant for disposal in basement areas.

7.2 Considerations on selection of investigation sites

The presented area characterizations and evaluations provide the geological basis for the selection of two investigation sites which will be chosen through a dialogue process managed by MHES. For the site selection, socio-economic and other relevant criteria will be used in addition to the geological, safety-based criteria.

When selecting the specific investigation sites and their areal extent, it is important to ensure that major features such as buried valleys, faults and other subsurface discontinuities are absent in the area. It may be necessary to revisit the seismic interpretation of the site of interest in order to evaluate whether further surface or subsurface data are required for the delineation of a specific investigation site. If the existing data coverage is insufficient to provide the required level of detail, additional geophysical or other relevant data should be acquired as part of the site delineation process, in order to reduce the risk of encountering major discontinuities during the detailed site investigation.

For the selection and areal delineation of specific investigation sites, it is necessary to know the specific geological requirements and criteria related to the identified (preliminary) disposal concept. This is to ensure that all relevant and critical geological data required for the site characterization and a safety case are collected prior to a potential decision on whether to dispose the waste at the site. The geological criteria should include a specification of the rock volume necessary for disposal, including the repository size and dimensions, and any shafts, tunnels and / or deviated boreholes that need to be constructed in order to fill the waste into the subsurface repository.

A preferable situation for an investigation site is that existing data indicates a high chance of encountering the required favourable rock properties and conditions from the site investigations. A site should be chosen where data indicate that the potential host rock and the ECZ are laterally extensive without significant discontinuities for at least 5x5 kilometers. This is to ensure that:

- There is some lateral flexibility for the precise location of a potential repository in case detailed investigations identify significant subsurface discontinuities within the site.
- In case faults are identified near a potential investigation site it is important to acknowledge the uncertainty on fault mapping to reduce the risk of drilling into a fault during the site investigations. The lateral extension of fault planes identified on 2D seismic lines are highly uncertain in areas where large distance between seismic lines does not allow for mapping with high confidence.
- The drilling of boreholes to depths of more than 500 meters should be carried out at the fringe of the site in order not to compromise barriers in the central parts of the

site where a repository might be established in the future. To ensure that data acquired from the boreholes are highly representative for the central part of the site, it is important that the geological record and rock properties can be assumed to be consistent within the entire investigation site.

Final comments regarding selecting and outlining investigation sites

The purpose of the geological siting project is to map and characterize the subsurface properties and conditions at depths to 500 meters, in order to identify potentially suitable sites for deep geological disposal of Danish radioactive waste. The result of the siting project's first phase shows that large areas may be suitable for selection of sites for detailed investigations in the project's next phase (Table 7.1). In these areas it is expected that the geological properties and conditions, as required by B90 (Danish Parliament, 2018) and recommended by international guidelines are likely to be confirmed from site specific investigations.

If it is decided to select an investigation site in an area where the horizontal continuity (a property for criterion 1.1) and natural stability (criterion 2.1) are less favourable, further detailed and time consuming investigations are required to map and outline a suitable investigation site. Additionally, in these areas there is a risk that favourable properties and conditions cannot be confirmed from the detailed site investigations.

In areas where sand layers potentially acting as fairways to flow are identified at depths around or just below 500 meters (criterion 1.4 is scored as less favourable) it will be challenging to identify suitable investigation sites without flow fairways. This is because the thickness of individual sand layers is typically in the range of 1–10 meters, which is below seismic detection and resolution, and the lateral extension of relatively thin sand layers cannot be mapped based on seismic data. The presence of flow paths in these areas is a risk which may be tested by drilling of deep boreholes, however numerous wells might be needed to ensure the area is without flow pathways. The potential safety impact and risk of vertical transport of nuclides by flow in areas with sand layers is at present poorly known and might be investigated further by 2D and 3D scenario modelling in the project's next phase. Likewise, the potential impact that water flow may have on the engineered barriers' functionality may be investigated

If a site is considered for selection in an area where carbonates in the ECZ do not have the required thickness of 250 meters (criterion 1.1 regarding spatial distribution is less favourable), it may be investigated by conceptual numerical modelling whether the actual carbonate thickness in combination with the host rock properties and preliminary concepts for engineered barriers are likely to provide the required barrier effectiveness. Geochemical retardation of nuclides should be included in the modelling as it will contribute to the geological barrier effectiveness. Alternatively, it might be considered whether disposal deeper than 500 meters is an option, which could provide a sufficiently thick section of low permeabilty rock in the ECZ.

The geological criteria that have been used for evaluation of the areas are defined based on the assumption that all Danish radioactive waste must be disposed in one repository. This is to ensure that sites investigated in the project's next phase will be suitable for disposal of all the waste. At present a specific disposal concept has not yet been selected by DD but several potential designs are identified (Danish Decommissioning, 2021). The concepts range from disposal of a minor part of the waste (including the special waste) in a deep borehole combined with shallower geological disposal of the LLW, to a concept where all the waste is disposed in one repository at 500 meters depth. The final concept design will depend on the subsurface geology at the site, which should comply with the necessary safety standards required by the waste inventory (Blechschmidt et al., 2021, Appendix B). For planning of the site investigation program, it is important that requirements related to a specific (preliminary) disposal concept have been identified. This is to ensure that the necessary and critical information for a safety evaluation and a subsequent decision on whether to dispose waste at the site is available.

The present evaluation is made based on the assumption that all the Danish radioactive waste will be disposed in one deep repository, which requires a large volume of homogeneous host rock. However, if a different concept is chosen, for example a deep borehole solution for a minor part of the waste, then it is possible that some of the criteria on spatial extent that are scored as orange may be scored differently, either as potentially suitable, or suitable (yellow or green). Likewise, an area with an orange score, given due to the lack of a sufficient thickness of carbonate in the ECZ, may potentially be suitable for disposal if a repository can be placed at a depth greater than 500 meters, or if the combined site specific properties can be demonstrated to provide the necessary geological barriers. Disposal at depths exceeding 500 meters might be feasible in a borehole solution. A concept where all the Danish radioactive waste is disposed of at greater depths is expected to be geotechnically complex and may not be feasible. As mentioned from the review process (Blechschmidt et al. 2021, Appendix B), the disposal concept should be targeted the relatively small volumes and radioactive hazard of the waste inventory.

The geological investigations of two sites in the project’s next phase will provide detailed data on the subsurface properties and conditions at depths to 500 meters. The acquired data will be used as input to a safety case with the purpose of demonstrating whether the combined disposal concept of geological and engineered barriers can provide the required level of safety and performance on both the short and long term. If some of the geological properties and conditions of the site are scored as less favourable, it should be investigated whether other geological properties can be expected to compensate, and/or whether the disposal concept and the engineered barriers may be designed to mitigate the issue. If suitable geological properties cannot be demonstrated at the site, and the issues cannot be mitigated by engineering, the conclusion of the site investigation may be that the site cannot provide the required properties for safe geological disposal of the Danish radioactive waste.

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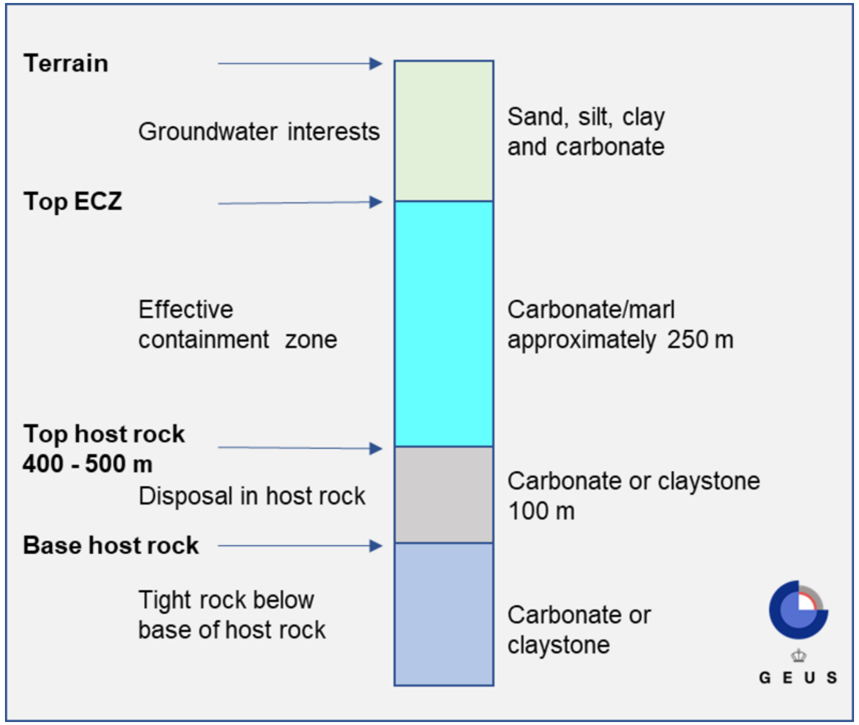
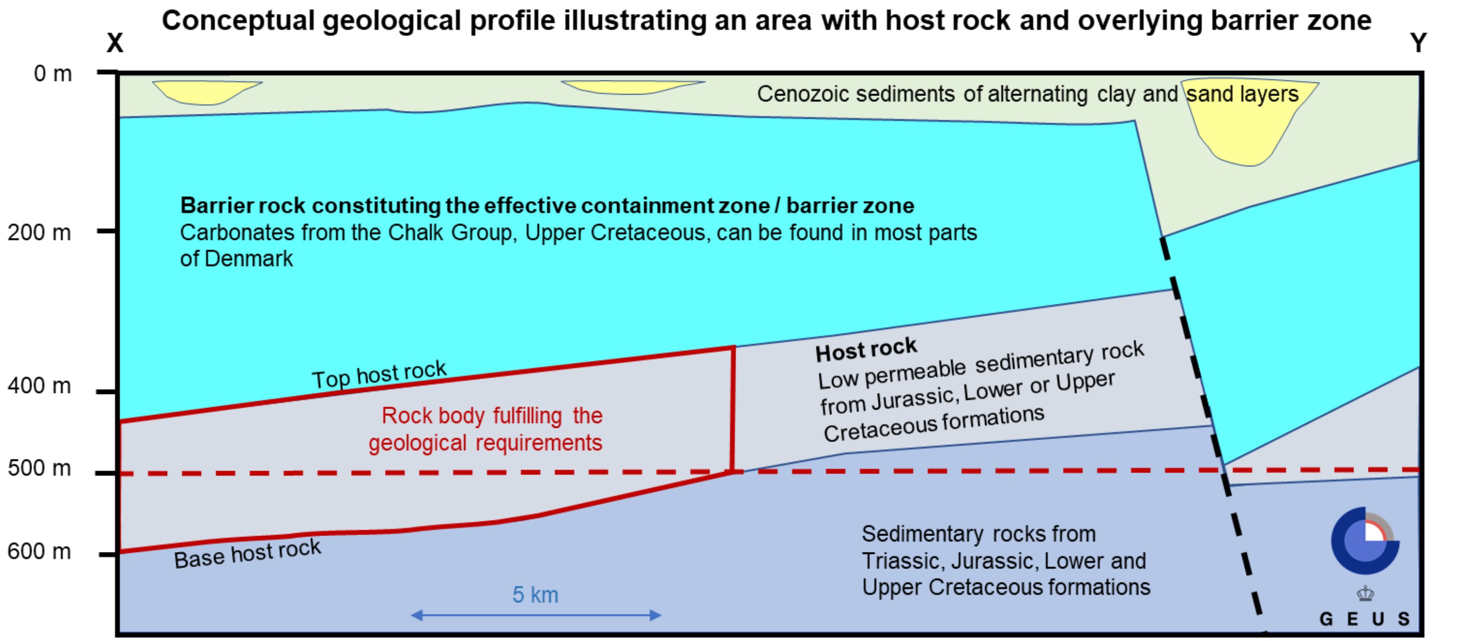
Concepts for scoring of properties and criteria - I

Definitions:	Host rock (min. 100 m thick)	Barrier rock (ECZ) (approximately 250 m thick)
	• Claystone (Lower Cretaceous and Jurassic) • Carbonate (Upper Cretaceous) • Granite/gneiss (Precambrian)	• Carbonate (Upper Cretaceous) From top of host rock and upwards



Conceptual geologic succession based on average conditions in the Danish subsurface (bed rock excluded)



Conceptual geologic cross section illustrating a mapped potential body of host rock at 500 meters depth

Concepts for scoring of properties and criteria - II

Scoring of properties related to criteria:

- Data indicate that unfavorable properties or conditions predominate in the area

+ Data indicate potentially favorable properties and conditions, or data from analogs indicate favorable properties can be expected

++ Data from the area indicate predominantly properties and conditions are expected to occur

Comments:

- The total score of a criterion represents a qualitative assessment of the sub-criteria scoring (not a numerical calculation)
- Some sub-criteria are weighted higher than others. An example is the host rock properties which weigh higher than properties for rock properties of barriers in the overlying ECZ as all the requirements given in B90 are related to the host rock properties. The scoring of criterion 1.1 depends on the presence of both a low permeable host rock (100 meters thick) AND low permeable rocks in the ECZ both fulfilling the thickness requirements and continuous lateral extension. If one of these parameters is unfavorable, the criterion will be scored as unfavorable regardless of the presence of other favourable properties (if for example the host rock is less than 100 meters thick, and all other sub-criteria are favourable)
- Geological conditions with potential influence on the geotechnical properties will be addressed in general terms, but specific properties such as rock strength, compressibility, and others, will not be addressed in this phase as data from 500 meters depth are absent. The evaluation is based on the prerequisite, that one possible scenario is to dispose all the waste at 500 meters depth which is a solution that requires a significant volume of geotechnically competent rocks. If disposal in a borehole is decided, this solution will require a smaller facility. In this case, some of the requirements on lateral extent of host rocks and barriers may be revised which may possibly result in some additional areas being favourable for disposal
- The scoring of each parameter is accompanied with comments where relevant, as for example if the parameter varies significantly within the area

Concepts for scoring of properties and criteria – III

Score	Data support
Suitable	Reliable data show predominantly favourable properties
Potentially suitable	Data and / or analogues indicate that favourable properties are expected to be present, however with some uncertainty
Less suitable	Reliable data show that geological properties and conditions generally do not fulfil the criteria

A green score of a criterion indicates that the required properties are predominantly favorable, and that the assessment is based on the presence of representative and reliable data (good quality). This means that the favorable properties are widespread in most of the area, and the expectation is that it will be possible to find investigation sites with favorable properties. The risk that the acquisition of new data in the area will demonstrate the presence of less favorable properties is small.

A yellow score of a criterion indicates that most of the required properties are considered favorable, however based on limited data and / or data from geological models and analogues (same type of rock and / or geological framework) presented in the literature. A yellow score means that the evaluation in general is more uncertain. Future data acquisition is expected to confirm the presence of favorable properties, but there is a certain risk that favorable properties will not be demonstrated from new data.

An orange score means that the required properties related to a criterion are generally considered to be less favorable. The score is based on reliable and representative data, showing that the geological conditions and properties are less favorable and generally do not meet the defined criteria. The extent to which the properties are unfavorable will depend on the repository concept and the engineered barriers.

1. Properties of host rock and containment zone

Area: Nordjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Carbonate thickness exceeds 100 m, except north of the Frederikshavn-1 well, where it thins and disappears towards the north
	• Host rock occurs at around 500 m depth	+		
	• Host rock has a lateral extent of 5x5 km or more	+		Numerous large faults with vertical as well as lateral displacement are identified
	• Host rock is lithologically homogenous (vertically and laterally)	+		At 400-500 m depth, the carbonates from various stratigraphic levels occur due to dipping layers
	• Barrier rock is 250 m thick	-		*1) The carbonate section is 0-200 m thick in the 150-400 m depth range
	• Barrier rock has a lateral extent of 5x5 km or more	+		Many faults identified
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		The carbonates have a varying clay content
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		The presence of numerous clay layers is indicated from petrophysical logs
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		The presence of numerous clay layers is indicated from petrophysical logs
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		The carbonates contain clay layers
	• Host rock contains smectite	++		Smectite identified in core (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain clay layers
	• Barrier rock contains smectite	++		Smectite identified in core (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		
	• Laterally widespread, high-permeable layers are absent directly below host rock (at apprixímately 500 m depth)	+		Alternating layers of silt, clay and sand occutr in the upper part of the Lower Cretaceous section (in Frederikshavn-1 well)
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not observed

* 1) Required depth and thickness of the carbonates can only be found in the southernmost area of Nordjylland. Furthest to the north, the carbonate section pinches out due to erosion.

2. Natural stability

Area: Nordjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Some faults extend into the Cenozoic section Several earthquakes are recorded The area is located adjacent to the Sorgenfrei-Tornquist Zone
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ ++ ++		

3. Geotechnical feasibility

Area: Nordjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified • The host rock contains smectite or precipitated calcite in fractures • In the host rock, unconsolidated sand and fractures are absent • The barrier rock contains smectite or precipitated calcite in fractures • In the barrier rock, unconsolidated sand and fractures are absent • The barrier rock does not contain thick layers of plastic clay	+ + + + + ++		Layers in the carbonate section dip approximately 100 m pr 4-5 km (up to 2 %) Calcite precipitation in fractures is observed in core from the Erslev wells Calcite precipitation in fractures is observed in core from the Erslev wells
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability • Large open fractures or faults extending from the surface to more than 500 m are absent	+ +		

4. Possibility to acquire reliable new data

Area: Nordjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	-	(yellow)	Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	-		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+	(yellow)	Layer thickness and lithological contrast between layers in the carbonate section may be near or below the limit of seismic resolution
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		The boundary from L. to U. Cretaceous is a gradual lithological transition which results in uncertainty on seismic mapping of Base Chalk Group
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++	(green)	
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Nordjylland
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		The combined thickness of the L. Cretaceous and Jurassic sections exceeds 500 m
	• Host rock occurs at around 500 m depth	+		The L. Cretaceous – Jurassic section occurs at 400-500 m depth in the central and southern parts of Limfjord Øst
	• Host rock has a lateral extent of 5x5 km or more	+		Several faults are mapped, both normal and transverse faults
	• Host rock is lithologically homogenous (vertically and laterally)	-		The L. Cretaceous – Jurassic section consists of alternating layers of clay, silt and fine sand (e.g. Børglum-1, L. Cret.)
	• Barrier rock is 250 m thick	-		*1) The carbonate section is 0-200 m thick in the 150-400 m depth range
	• Barrier rock has a lateral extent of 5x5 km or more	+		
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Layers have highly varying clay content
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		Clay mineral content is variable
	• Host rock contains smectite	++		Smectite identified in Fjerritslev Fm. (Frederikshavn-1, core)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain clay, indicated by petrophysical logs
	• Barrier rock contains smectite	++		Smectite identified in Chalk Group (Sæby-1, core)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	-		Sand layers in the L.Cretaceous-Jurassic section are identified in core and from well logs (Frederikshavn-1)
	• Laterally widespread, high-permeable layers are absent directly below host rock (at apprixmately 500 m depth)	-		A 100 m thick section of Frederikshavn Fm. sandstone occurs below the L. Cretaceous claystone (Frederikshavn-1)
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

* 1) The required depth and thickness of carbonates forming barriers in the ECZ occur only in the southernmost part of the area. To the north, the Chalk Group pinches out due to uplift and erosion.

2. Natural stability

Area: Nordjylland
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Some faults extend into the Cenozoic section Several earthquakes are recorded The area is located adjacent to the Sorgenfrei-Tornquist Zone
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ ++ +		Calcite identified in the L. Cretaceous sediments (cuttings, Fjerritslev-2), but not in the Jurassic sediments

3. Geotechnical feasibility

Area: Nordjylland
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	-		The carbonate and claystone sections dip approximately 100 m pr 4-5 km (up to 2 %)
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		Sand aquifers are not observed in the Chalk Group
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

4. Possibility to acquire reliable new data

Area: Nordjylland
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	-		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	-		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Lithological transition from L. to U. Cretaceous is gradual causing uncertainty on seismic mapping of Base Chalk Group
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++		
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Limfjord Øst
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Carbonate thickness is 300 – 1000 m
	• Host rock occurs at around 500 m depth	++		Top Chalk Group occurs shallower than 100 m, Base Chalk at 500 m or deeper
	• Host rock has a lateral extent of 5x5 km or more	+		Locally limited continuity due to several faults and fault systems
	• Host rock is lithologically homogenous (vertically and laterally)	+		The carbonates have a highly varying clay content (indicated from petrophysical logs)
	• Barrier rock is 250 m thick	++		
	• Barrier rock has a lateral extent of 5x5 km or more	+		Locally limited continuity due to several faults and fault systems
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in carbonates (from petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay (petrophysical logs)
	• Host rock contains smectite	+		Smectite identified in core (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay (petrophysical logs)
	• Barrier rock contains smectite	+		Smectite identified in core (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		Possibility of karst in near-surface layers, where carbonates occur near or at ground level
	• Laterally widespread, high-permeable layers are absent directly below host rock (at apprixіmately 500 m depth)	-		*1) Alternating layers of silt, clay and sand comprise the upper part of the Lower Cretaceous section (Haldager-1 and Børglum-1)
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not mapped or expected

*1) Where Base Chalk Group occur at 500 meters depth there is a risk of L. Cretaceous sand occurring directly below the host rock interval (as seen in Haldager-1 and Børglum-1 wells).

2. Natural stability

Area: Limfjord Øst
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Several faults are identified. Several small earthquakes are registered. Limfjord Øst is situated in the Sorgenfrei – Tornquist Zone
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ ++ ++		

3. Geotechnical feasibility

Area: Limfjord Øst
Host rock: carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not observed

4. Possibility to acquire reliable new data

Area: Limfjord Øst
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable infomation on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Layer thickness and lithological contrast between layers in the carbonate section may be near og below the limit of seismic resolution
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++		
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Limfjord Øst
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Thickness is 200-1000 m
	• Host rock occurs at around 500 m depth	+		Only in the central part of the area
	• Host rock has a lateral extent of 5x5 km or more	-		Many faults identified
	• Host rock is lithologically homogenous (vertically and laterally)	-		Numerous sand and silt layers (core data, Haldager-1)
	• Barrier rock is 250 m thick	++		
	• Barrier rock has a lateral extent of 5x5 km or more	-		*1) Many faults
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in carbonate (from petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		Clay mineral content is variable
	• Host rock contains smectite	++		Smectite identified in Rødby Fm and Fjerritslev Fm (Core from Fjerritslev-2)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay
	• Barrier rock contains smectite	++		Smectite identified in core samples (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	-		* 2) Numerous sand layers occur in the L. Cretaceous section; possibly highly permeable allowing water flow
	• Laterally widespread, high-permeable layers are absent directly below host rock (at apprixImately 500 m depth)	-		Sand layers occur in the L. Cretaceous section including depths around 500 m
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not mapped or expected

*1) Faults in the carbonate section are common in areas where the host rock is L. Cretaceous – Jurassic claystone.
*2) In Haldager-1, sand layers occur in the L. Cretaceous section in the depth interval 200-800 m.

2. Natural stability

Area: Limfjord Øst
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Several faults are identified and mapped. Earthquakes are registered. Limfjord Øst is situated in the Sorgenfrei – Tornquist Zone
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ ++ +		Calcite identified in the L. Cretaceous (cuttings, Fjerritslev-2), but not from analysis of the Jurassic sediments

3. Geotechnical feasibility

Area: Limfjord Øst
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	+		Varying dip, especially above inversion structures
	• The host rock contains smectite or precipitated calcite in fractures	+		
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in cores from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		Sand aquifers are not observed in the Chalk Gr. Possibility of shallow karst in near-surface layers; deep karst is not observed nor expected
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not mapped or expected, if present they can be identified and mapped during site investigations

4. Possibility to acquire reliable new data

Area: Limfjord Øst
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+	(green)	L. Cretaceous stratigraphy at 500 m depth varies over relatively short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		Stratigraphy of carbonates at 500 m depth varies over relatively short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+	(yellow)	The gradual lithological transition from the Lower to the Upper Cretaceous cause uncertainty on seismic mapping of Base Chalk Gr.
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+		The area is intersected by the fjord Limfjorden. If karst occur locally, it may influence the quality of new seismic data
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++	(green)	
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Midt-Vestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Chalk Gr. thickness is 500-1000 m
	• Host rock occurs at around 500 m depth	++		*1) In most of the area carbonates occur at 500 m depth
	• Host rock has a lateral extent of 5x5 km or more	+		Area is influenced by salt tectonics
	• Host rock is lithologically homogenous (vertically and laterally)	+		Due to structural complexity and dipping beds varying stratigraphic intervals of the Chalk Gr. occur at 500 m depth
	• Barrier rock is 250 m thick	-		In most of the area Top Chalk Gr. occurs at 300-500 m depth
	• Barrier rock has a lateral extent of 5x5 km or more	+		Several faults identified and mapped
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying stratigraphic intervals of the Chalk Gr. occur at specific depths due to structural complexity and dipping layers
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		The Chalk Gr. carbonates contain variable amounts of clay
	• Host rock contains smectite	+		Smectite identified in core (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The Chalk Gr. carbonates contain variable amounts of clay
	• Barrier rock contains smectite	+		Smectite identified in core (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	+		
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not obseved

*1) In most of Midt-Vestjylland Top Chalk Group occurs at depth from 200 m (northern area) to 500 m (in central parts). Towards SW, Top Chalk Group occurs at 500 m or deeper.

2. Natural stability

Area: Midt-Vestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	- ++		*1) Frequent earthquakes registered off-shore, some onshore. Area is situated adjacent to Sorgenfrei – Tornquist Zone and is characterized by salt tectonics
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		Most of the area is without TEMdata
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

*1) Many small earthquakes have been registered in the area as well as adjacent off-shore areas. Only few faults have been mapped to extend into the Cenozoic section. Numerous salt diapirs and other salt structures occur, some possibly with ongoing salt remobilisation. In the easternmost part of Midt-Vestjylland salt diapirs are absent and formations are in general more laterally continuous due to less structural complexity.

3. Geotechnical feasibility

Area: Midt-Vestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	-		Thickness and depth of formations vary significantly over short distances, particularly adjacent to salt diapirs
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		*1)
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not mapped or expected

* 1) Locally in southern parts of the area where the Cenozoic section is very thick, there may be a risk of plastic clay, but the Cenozoic section is not regarded as part of the ECZ.

4. Possibility to acquire reliable new data

Area: Midt-Vestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+	(yellow)	*1) Large variation of thickness and stratigraphy at 500 m depth occur within relatively short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		*1) Large variation of thickness and stratigraphy at 500 m depth occur within relatively short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+	(yellow)	Layer thickness and lithological contrast between layers in the the carbonate section may be near or below the limit of seismic resolution
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+		The marine inlet Limfjorden extends across the area Locally occurring karst may influence the quality of new seismic data
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++	(green)	
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

* 1) Due to highly varying thicknesses of, and depths to formations within short distances, it may be challenging to identify investigation sites with uniform geological formations extending for several kilometers, except for the very eastern part of the area.

1. Properties of host rock and containment zone

Area: Østjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++	(green)	Carbonate section has a thickness of more than 750 m
	• Host rock occurs at around 500 m depth	++		Constitute the rock type in most of the interval 0-500 m
	• Host rock has a lateral extent of 5x5 km or more	++		Numerous minor faults with no apparent off-set occur in the carbonate section; no influence on horizontal rock continuity
	• Host rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in carbonates (from petrophysical logs)
	• Barrier rock is 250 m thick	+		Carbonate thickness is 250 m in the NE, however, Top Chalk occurs deeper than 200 m in the SW and constitiute less than 250 m barrier rock in the ECZ
	• Barrier rock has a lateral extent of 5x5 km or more	++		Few large faults are mapped to extend into the Cenozoic section
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content of the carbonates (petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+	(yellow)	
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+	(yellow)	The carbonate section contains variable amounts of clay
	• Host rock contains smectite	+		Smectite identified in core samples (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonate contains variable amounts of clay
	• Barrier rock contains smectite	+		Smectite identified in core samples(Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+	(yellow)	
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	+		
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

2. Natural stability

Area: Østjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Several faults extend to Top Chalk Group (near terrain)
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however large areas are without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

3. Geotechnical feasibility

Area: Østjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	+		
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		*1) Plastic clay does not occur in the carbonatesection
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		In the southern Østjylland area sandy Cenozoic deposits overlie the carbonates at depths varying from 200 to 400 meters (and do not contribute to the ECZ)
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

*1) Layers of plastic clay may occur in the Cenozoic section, which is 200-400 m thick in the southern part of the area.

4. Possibility to acquire reliable new data

Area: Østjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++ ++ ++ ++		Horizontally continuous stratigraphy and properties is expected Horizontally continuous stratigraphy and properties is expected Well data will provide reliable information on vertical variations Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data • Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+ ++		Layer thickness and lithological contrast between layers in the carbonate section may be near or below the limit of seismic resolution
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped • Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++ ++		

1. Properties of host rock and containment zone

Area: Sydvestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		
	• Host rock occurs at around 500 m depth	++		Carbonates occur in the 200-500 m depth interval; overlying is the Cenozoic section of interbedded sand and clay
	• Host rock has a lateral extent of 5x5 km or more	++		Minor faults are identified with no or very minor off-set
	• Host rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates
	• Barrier rock is 250 m thick	-		*1) In most of the area, the carbonate section is less than 250 meters in the ECZ (Top Chalk Group occurs at 200-500 m)
	• Barrier rock has a lateral extent of 5x5 km or more	++		
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Carbonates have a varying clay content
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay
	• Host rock contains smectite	+		Smectite identified in core (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay
	• Barrier rock contains smectite	+		Smectite identified in core (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	+		
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

*1) It may be investigated whether a Cenozoic clay dominated section locally constitutes the required thickness to form a barrier rock immediately overlying the carbonate host rock at a site of potential interest for disposal, however, generally numerous sand layers occur in the Cenozoic sections and detailed mapping will be needed.

2. Natural stability

Area: Sydvestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	++ ++		
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

3. Geotechnical feasibility

Area: Sydvestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical Properties and conditions	• The geological formations are horizontally or near-horizontally stratified	+		
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		*1) No plastic clay identified in the carbonate section
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		In the southern part of the area the sandbearing Cenozoic section constitute the depth interval from 200 to 500 m.
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

*1) Plastic clay layers may occur in the Cenozoic section, which is 200-500 m thick in the area.

4. Possibility to acquire reliable new data

Area: Sydvestjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++ ++ ++ ++		Horizontal to near-horizontal, hence, relatively good lateral prediction of stratigraphy and properties is expected Horizontal to near-horizontal, hence, relatively good lateral prediction of stratigraphy and properties is expected Well data will provide reliable information on vertical variations Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data • Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+ ++		Layer thickness in the Chalk Gr. can be near og below the limit of seismic resolution, and lithological contrasts may be too small to enable detailed mapping of clay rich layers
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped • Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++ ++		

1. Properties of host rock and containment zone

Area: Sønderjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Thickness is generally around 500 m
	• Host rock occurs at around 500 m depth	+		Top Chalk Group occurs at 200-600 m depth or deeper
	• Host rock has a lateral extent of 5x5 km or more	-		Numerous faults identified
	• Host rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates (petrophysical logs)
	• Barrier rock is 250 m thick	-		*1) Carbonate as a barrier rock is maximum 100 m thick in the ECZ
	• Barrier rock has a lateral extent of 5x5 km or more	-		Many faults occur
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates (petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay
	• Host rock contains smectite	+		Smectite identified in core (Sæby-1)
	• Barrier rock matrix has a high content of clay minerals	+		The carbonates contain variable amounts of clay
	• Barrier rock contains smectite	+		Smectite identified in core (Sæby-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	+		
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

*1) It may be investigated whether a Cenozoic clay dominated section locally constitute the required thickness to form a barrier rock immediately overlying the carbonates in the area, however, generally Cenozoic section comprise numerous sand layers and very detailed mapping will be needed to map potential thick bodies of claystone.

2. Natural stability

Area: Sønderjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	++ ++		
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

3. Geotechnical feasibility

Area: Sønderjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	+		Dipping layers occur, particularly adjacent to salt ridges
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		*1) No plastic clay in the carbonates
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		In the southern part of the area the sandbearing Cenozoic section constitutes most of the depth interval from 200-500 m (not considered to contributie to the ECZ)
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

*1) Layers of plastic clay may occur in the Cenozoic section, which is 200-500 m thick in the area.

4. Possibility to acquire reliable new data

Area: Sønderjylland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+		Due to dipping layers, different stratigraphic intervals occur at 500 m depth within short distances
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Layer thickness and lithological contrast between clay rich layers in the Chalk Group may be near or below the limit of seismic resolution
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++		
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Fyn
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more • Host rock occurs at around 500 m depth • Host rock has a lateral extent of 5x5 km or more • Host rock is lithologically homogenous (vertically and laterally) • Barrier rock is 250 m thick • Barrier rock has a lateral extent of 5x5 km or more • Barrier rock is lithologically homogenous (vertically and laterally)	+ + + + + + + + + + + +		carbonate thickness exceeds 500 m Top Chalk Group occurs at 100-200 m depth Few faults identified and mapped Varying clay content in carbonate (based on petrophysical logs) Top Chalk Group occurs at 100-200 m depth Few faults identified and mapped Varying clay content in the carbonate sediments (based on petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport) • Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+ +		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals • Host rock contains smectite • Barrier rock matrix has a high content of clay minerals • Barrier rock contains smectite	+ + + +		Varying clay content in the carbonate sediments (petrophysical logs) Smectite identified in core samples (Stevns-1) Varying clay content in the carbonate sediments (based on petrophysical logs) Smectite identified in core samples (Stevns-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock • Laterally widespread, high-permeable layers are absent directly below host rock (at apprixmately 500 m depth) • Laterally widespread, high-permeable layers are absent in barrier rock • Large open fractures, extending from host rock to the top of the barrier rock, are absent	+ + + +		Open fractures or faults are not mapped or expected

2. Natural stability

Area: Fyn
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glcio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ + + +		Very few earthquakes are registered; Fyn is situated on the tectonically stable Ringkøbing – Fyn High
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		Extensive data coverage indicates that there are valleys in large parts of the area
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + + +		

3. Geotechnical feasibility

Area: Fyn
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		Very low angle dipping formations in the area
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells. Smectite identified in core (Stevns-1)
	• In the host rock, unconsolidated sand and fractures are absent	+		Calcite precipitation in fractures is observed in core from the Erslev wells
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Smectite identified in core (Stevns-1)
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

4. Possibility to acquire reliable new data

Area: Fyn
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	+ +		Horizontal to near-horizontal dipping beds, hence, good lateral prediction of properties is expected
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to near-horizontal dipping beds, hence, good lateral prediction of properties is expected
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	+ +		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	+ +		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Layer thickness in the carbonate section may be below seismic resolution. The gradual lithological transition from Lower to Upper Cretaceous may cause uncertainty on seismic mapping of Base Chalk Gr.
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+ +		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	+ +		Large faults can be mapped, salt is not present in the area
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	+ +		

1. Properties of host rock and containment zone

Area: Sydlige Øhav
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		Thickness is 400-500 m or more
	• Host rock occurs at around 500 m depth	+		*1)
	• Host rock has a lateral extent of 5x5 km or more	+		*2) Many faults, but also areas without faults
	• Host rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in carbonate (based on petrophysical logs)
	• Barrier rock is 250 m thick	++		
	• Barrier rock has a lateral extent of 5x5 km or more	+		*2) Many faults, but also areas without faults
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates (from petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		Varying clay content in carbonate (based on petrophysical logs)
	• Host rock contains smectite	+		Smectite identified in core (Stevns-1)
	• Barrier rock matrix has a high content of clay minerals	+		Varying clay content in carbonate (based on petrophysical logs)
	• Barrier rock contains smectite	+		Smectite identified in core (Stevns-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+		
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	-		Sand layers occur in L. Cretaceous, and since Top L. Cretaceous is at 400-600 m depth, sand layers may occur directly below host rock
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Deep faults may continue to near-terrain

*1) In parts of the area (particularly to the east), where Base Chalk Group occurs at 400-500 m depth the L. Cretaceous – Jurassic claystones may be an alternative potential host rock.
*2) In areas where Base Chalk Group occurs at greatest depths (500-600 m) fewest faults are identified.

2. Natural stability

Area: Sydlige Øhav
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Some faults continue into the Cenozois section to near-terrain levels. Very few earthquakes are registered
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	++		Extensive TEM data coverage indicates that most of the area is without buried valleys
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

3. Geotechnical feasibility

Area: Sydlige Øhav
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		Locally, steeply dipping layers close to faults
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells. Smectite identified in core samples (Stevns-1)
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells Smectite identified in core (Stevns-1)
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified

4. Possibility to acquire reliable new data

Area: Sydlige Øhav
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Layer thickness in the carbonate section may be below the limit of seismic resolution. The gradual lithological transition from Lower to Upper Cretaceous may cause uncertainty on seismic mapping of Base Chalk Gr.
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++		
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Sydlige Øhav
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++		*1) The L. Cretaceous section is thinner than 50 m, combined with the Jurassic section the thickness is 100-1000 m
	• Host rock occurs at around 500 m depth	++		Top L. Cretaceous occurs at depths of 400-600 m
	• Host rock has a lateral extent of 5x5 km or more	+		Locally numerous faults. The Jurassic section occurs in half-grabens bounded by normal faults
	• Host rock is lithologically homogenous (vertically and laterally)	-		*2) L. Cretaceous – Jurassic sections comprise interbedded clay, marl, sand and silt
	• Barrier rock is 250 m thick	++		Top Chalk Gr. occurs at depths around 100 m, thus a significant thickness of carbonates in the ECZ
	• Barrier rock has a lateral extent of 5x5 km or more	+		Numerous faults identified
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in carbonates (based on core samples from Stevns-1 and petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+		Varying lithologies with varying clay content
	• Host rock contains smectite	++		High content of smectite in the Fjerritslev Fm, varying amounts in L. Cretaceous sediments (core data Rødby-1 and Ørslev-1)
	• Barrier rock matrix has a high content of clay minerals	+		Varying clay content in carbonates (petrophysical logs)
	• Barrier rock contains smectite	+		Smectite identified in core sampls (Stevns-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	-		Sand layers of varying thickness, up to 10 m thick or more
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	-		Gassum Fm sandstone occurs at base Jurassic with gradual transition
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

*1) L. Cretaceous section is horizontally widespread but very thin. Jurassic sediments occur in half-grabens 5-10 km wide, thus a great variation in claystone thickness over short distances.
*2) The L. Cretaceous - Jurassic sections consist of interbedded 10-40 m thick layers of sand, silt, marl and claystone (well logs and cores), the proportions are expected to vary laterally.

2. Natural stability

Area: Sydlige Øhav
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Some faults observed to continue into the Cenozoic section to near-terrain. Only few earthquakes are registered
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	++		Extensive TEM data coverage indicates that most of the area is without buried valleys
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ + -		Smectite identified in core (Rødby-1, Ørslev-1) Smectite identified in core (Stevns-1) Limited number of samples indicate calcite is absent

3. Geotechnical feasibility

Area: Sydlige Øhav
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	-		L. Cretaceous is horisontally bedded, Jurassic sections are dipping due to preservation in tilted fault blocks
	• The host rock contains smectite or precipitated calcite in fractures	+		
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells Smectite identified in core (Stevns-1)
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not mapped or expected

4. Possibility to acquire reliable new data

Area: Sydlige Øhav
Host rock: Claystone, L. Cretaceous and Jurassic

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	-	(green)	L. Jurassic thickness varies significantly from north to south within a few km perpendicular to the W-E trending axis of half-grabens
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to low angle dipping layers in the carbonate section, good lateral prediction of properties is expected
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable infomation on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+	(yellow)	Layer thickness in the carbonate section may be below the limit of seismic resolution. The gradual lithological transition from Lower to Upper Cretaceous may cause uncertainty on seismic mapping of Base Chalk Group
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++	(green)	
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Sydvestsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++	green	Chalk Gr. carbonates have thicknesses of 500-1250 m
	• Host rock occurs at around 500 m depth	++		Top Chalk Group occurs at 100-300 m depth
	• Host rock has a lateral extent of 5x5 km or more	++		Very few faults are identified
	• Host rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates (based on Stevns-1 core data and petrophysical logs)
	• Barrier rock is 250 m thick	+		*1) In SE part of the area Top Chalk Group occurs at 0-150 m, and carbonates constitute the barrier rock i the ECZ
	• Barrier rock has a lateral extent of 5x5 km or more	++		Very few faults are identified
	• Barrier rock is lithologically homogenous (vertically and laterally)	+		Varying clay content in the carbonates (based on Stevns-1 core data and petrophysical logs)
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	+	yellow	
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	+	yellow	Varying clay content (based on petrophysical logs)
	• Host rock contains smectite	+		Smectite identified from core samples (Stevns-1)
	• Barrier rock matrix has a high content of clay minerals	+		Varying clay content (based on petrophysical logs)
	• Barrier rock contains smectite	+		Smectite identified from core samples (Stevns-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+	yellow	
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	+		Carbonates occur at depths exceeding 500 meters and sand layers are not expected
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		Open fractures or faults are not identified

*1) In northwestern part of the area, Top Chalk Gr. occurs at depths of 200-450 m, and the Cenozoic section is 200-450 thick, thus the carbonate section in the ECZ is less than 250 m thick

2. Natural stability

Area: Sydvestsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+ ++		Faults mapped to extend from Base Triassic/Top Zechstein salt into the Cenozoic section. Many earthquakes registered in northern part of area
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	++ ++ ++		Smectite identified in core samples (Stevns-1) Smectite identified in core samples (Stevns-1)

3. Geotechnical feasibility

Area: Sydvestsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells. Smectite identified in core (Stevns-1)
	• In the host rock, unconsolidated sand and fractures are absent	+		Calcite precipitation in fractures is observed in core from the Erslev wells. Smectite identified in core (Stevns-1)
	• The barrier rock contains smectite or precipitated calcite in fractures	+		
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		Plastic clay layers may occur in the Cenozoic section (Lillebæltsler) which is not considered as part of the ECZ
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Open fractures or faults are not identified Some major faults are mapped, but from limited seismic data coverage in the area

4. Possibility to acquire reliable new data

Area: Sydvestsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties • Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++ ++ ++ ++		Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected Well data will provide reliable information on vertical variations Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data • Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	+ ++		Layer thickness in the carbonate section may be below the limit of seismic resolution.
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped • Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++ ++		

1. Properties of host rock and containment zone

Area: Nordøstsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more • Host rock occurs at around 500 m depth • Host rock has a lateral extent of 5x5 km or more • Host rock is lithologically homogenous (vertically and laterally) • Barrier rock is 250 m thick • Barrier rock has a lateral extent of 5x5 km or more • Barrier rock is lithologically homogenous (vertically and laterally)	++ ++ ++ + ++ ++ +		Thicness is from 750 m to more than 1500 m Top Chalk Group occurs at 0-100 m depth Only few faults identified *1) Well logs show varying clay content in the carbonates Top Chalk Group occurs from near terrain to 100 m depth Few faults identified *1) Well logs indicate varying clay content in the carbonates
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport) • Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	+ +		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals • Host rock contains smectite • Barrier rock matrix has a high content of clay minerals • Barrier rock contains smectite	+ + + +		Varying clay content in carbonate (based on petrophysical logs) Smectite identified from core samples (Stevns-1) Varying clay content in carbonate (based on petrophysical logs) Smectite identified from core samples (Stevns-1)
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock • Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth) • Laterally widespread, high-permeable layers are absent in barrier rock • Large open fractures, extending from host rock to the top of the barrier rock, are absent	+ + + +		Open fractures or faults are not identified or expected

*1) In the Lavø-1 well, a clay dominated section occurs in the interval at 700-800 m depth in the Chalk Group

2. Natural stability

Area: Nordøstsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected • Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	- ++		Many earthquakes of small magnitude, also off-shore Several faults mapped to near surface, some continue into the Cenozoic section
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	+		SkyTEM data indicate valleys are absent in some areas, however, most of the area is without data
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock • Smectite and / or montmorillonite is present in the barrier rock • Calcite is present in the host rock	+ + ++		

3. Geotechnical feasibility

Area: Nordøstsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		
	• The host rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells Smectite identified from core samples (Stevns-1)
	• In the host rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Calcite precipitation in fractures is observed in core from the Erslev wells Smectite identified from core samples (Stevns-1)
	• In the barrier rock, unconsolidated sand and fractures are absent	+		
	• The barrier rock does not contain thick layers of plastic clay	++		
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		Faults extend from great depths to near terrain
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		

4. Possibility to acquire reliable new data

Area: Nordøstsjælland
Host rock: Carbonate, Chalk Group

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		Horizontal to low angle dipping layers, thus, good lateral prediction of properties is expected
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data will provide reliable information on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data will provide reliable information on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+		Layer thickness in the carbonate section may be below the limit of seismic resolution.
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		Parts of the area is covered by water bodies including Roskilde Fjord, Arre Sø, Esrum Sø
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++		
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

1. Properties of host rock and containment zone

Area: Bornholm
Host rock: Granite/gneiss, Precambrian

Criteria	Properties	Sub-score	Score	Comments
1.1 Spatial extent	• Host rock thickness is 100 m or more	++	(green)	Crystalline basement rocks occur from terrain or near terrain to great depths
	• Host rock occurs at around 500 m depth	++		
	• Host rock has a lateral extent of 5x5 km or more	++		
	• Host rock is lithologically homogenous (vertically and laterally)	++		
	• Barrier rock is 250 m thick	++		
	• Barrier rock has a lateral extent of 5x5 km or more	++		
	• Barrier rock is lithologically homogenous (vertically and laterally)	++		
1.2 Hydraulic barrier effectiveness	• Host rock has a very low permeability (promotes diffusion dominated nuclide transport)	++	(green)	Unweathered crystalline rocks, such as granite and gneiss, have extremely low permeability when fractures are absent
	• Barrier rock has a very low permeability (promotes diffusion dominated nuclide transport)	++		
1.3 Geochemical conditions for retardation	• Host rock matrix has a high content of clay minerals	-	(orange)	Granite and gneiss are relatively coarse grained without clay
	• Host rock contains smectite	-		Smectite has not been reported from granite and gneiss, nor from their weathering products
	• Barrier rock matrix has a high content of clay minerals	-		Granite and gneiss are relatively coarse grained without clay
	• Barrier rock contains smectite	-		Smectite has not been reported from granite and gneiss, nor from their weathering products or dykes
1.4 Release pathways	• Laterally widespread, high-permeable layers are absent in host rock	+	(yellow)	No data from 500 m depth. Horizontal fractures observed at 0-100 m depth with apparant increased spacing downwards. Crystalline rocks continue to depths exceeding 500 m
	• Laterally widespread, high-permeable layers are absent directly below host rock (at appriximately 500 m depth)	++		No data from 500 m depth. Horizontal fractures occur with increasing distance downwards in the interval 0-100 m
	• Laterally widespread, high-permeable layers are absent in barrier rock	+		Large open fractures or faults are not identified to extend downwards to 500 meters depth
	• Large open fractures, extending from host rock to the top of the barrier rock, are absent	+		

2. Natural stability

Area: Bornholm
Host rock: Granite/gneiss, Precambrian

Criteria	Properties	Sub-score	Score	Comments
2.1 Stability of the site and rock properties	• Frequency and magnitude of registered earthquakes is small, and reactivation of possible deep-seated faults is not expected	++		Very few earthquakes are registered. Bornholm is situated on a horst block, and in case of fault reactivation this will most likely take place along the bounding faults and not in the central part of the basement area on Bornholm
	• Glacio-tectonic deformation and vertical fracturing caused by future glaciation is expected to affect only formations close to terrain and the shallower parts of the barrier zone (depths of maximum 300 m below terrain)	+		Vertical, glacially induced fractures identified in the depth interval 0-50 m
2.2 Erosion	• Deep, buried, sand-filled Quaternary valleys are absent	++		Locally, fairly large, sandstone-filled associated occur associated to diabas dykes. These sandstone are tightly cemented
2.3 Repository induced influences	• Smectite and / or montmorillonite is present in the host rock	-		*1) Not identified in granite/gneiss or their weathering products
	• Smectite and / or montmorillonite is present in the barrier rock	-		*1) Not identified in granite/gneiss or their weathering products
	• Calcite is present in the host rock	-		*1) Not identified in granite/gneiss or their weathering products

*1) The nuclear waste is not expected to cause compaction which might be associated with generation of microfracturies in a host rock of crystalline rock, therefore, this criterion on self-healing potential of repository induced fractures is less relevant for crystalline rocks. Deep geological repositories are being established in granite/gneiss in Sweden and Finland, and the Danish project can learn from their experiences if needed.

Area: Bornholm
Host rock: Granite/gneiss, Precambrian

3. Geotechnical feasibility

Criteria	Properties	Sub-score	Score	Comments
3.1 Rock mechanical properties and conditions	• The geological formations are horizontally or near-horizontally stratified	++		Granite/gneiss is not layered or stratified, fractures cross-cut structures
	• The host rock contains smectite or precipitated calcite in fractures	-		Smectite and/or calcite has not been reported from granite and gneiss, nor from their weathering products
	• In the host rock, unconsolidated sand and fractures are absent	-		Fractures are identified at surface with varying spacing. Fracture frequency decrease with depth, but no data exist from depths exceeding 100 m Sandstone dykes are tightly cemented
	• The barrier rock contains smectite or precipitated calcite in fractures	+		Smectite and/or calcite has not been reported from granite and gneiss, nor from their weathering products
	• In the barrier rock, unconsolidated sand and fractures are absent	+		Fractures are identified on surface with varying distances between them. Fracture frequency decrease with depth. No data from depths exceeding 100 m Sandstone dykes are tightly cemented
	• The barrier rock does not contain thick layers of plastic clay	++		No data from depths exceeding 100 m
3.2 Underground access and drainage	• The barrier rock does not contain thick and laterally widespread sand aquifers or fractured zones with high permeability	+		Data from water wells (0-100 m) indicate very limited water flow in horizontal fractures
	• Large open fractures or faults extending from the surface to more than 500 m are absent	+		Large, open faults are not identified

4. Possibility to acquire reliable new data

Area: Bornholm
Host rock: Granite/gneiss, Precambrian

Criteria	Properties	Sub-score	Score	Comments
4.1 Ease of characterisation of the rock	• The host rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++	(green)	The subsurface distribution of the granite/gneiss types is unknown, however mineral variations are not expected to significantly influence the rock properties
	• The barrier rock has a uniform thickness and stratigraphy, so identical properties can be expected over larger areas	++		The subsurface distribution of various granite/gneiss types is unknown, not expected to have significant influence on properties of ECZ
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of the host rock properties	++		Well data (core and logs) will provide reliable data on vertical variations
	• Data from drill cores and borehole logging in new boreholes will provide detailed and reliable information on the homogeneity and variability of barrier rock properties.	++		Well data (core and logs) will provide reliable data on vertical variations
4.2 Explorability of spatial conditions	• Lithological contrasts in the subsurface enables detailed mapping of layers and boundaries, architecture and faults based on seismic and / or other geophysical data	+	(yellow)	Large vertical faults can be mapped at surface
	• Surface conditions, topography and depth to the saturated water zone allow the collection of high-resolution geophysical data	++		Locally the terrain is very steep, but with relatively small relief
4.3 Predictability of long-term changes	• Larger faults and salt diapirs can be identified and mapped	++	(green)	
	• Buried sand-filled Quaternary valleys can be mapped based on new geological and geophysical data	++		

Geological siting project on deep disposal of the Danish radioactive waste

Review of: Phase 1, report no. 8.

Criteria and requirements for identification of suitable disposal sites

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Contents

1. Introduction

This report summarises the findings of an external panel of work being undertaken by the Geological Survey of Denmark and Greenland (GEUS) in support of the siting of a deep geological disposal facility for radioactive waste in Denmark.

GEUS has been tasked by the Danish Parliament with identifying areas where the geological properties are potentially suitable for the safe disposal of radioactive waste. The task is being carried out in collaboration with the Danish Ministry of Higher Education and Science (MHES), the project owner, and Danish Decommissioning (DD), the organisation responsible for storing the radioactive waste until final disposal. The first phase of the work comprises a review of available in geological information in order to map and describe various properties of the rock types identified at depths around 500 metres and understand the natural processes which have the potential to influence the long-term geological stability.

In the first stage of the project GEUS developed geological requirements and defined criteria largely based on recommendations from IAEA and experiences from similar international projects. These criteria are to be used for identification and initial evaluation of geological settings and rock types suitable for a deep geological repository of the Danish radioactive waste. They have been documented in a draft report 'Geological siting project on deep disposal of the Danish radioactive waste, Phase 1, report no. 8: Criteria and requirements for identification of suitable disposal sites', dated 10th May 2021[1].

In order to build confidence in its approach GEUS has sought external scientific review of the procedure for the scientific evaluations as presented in the criteria report. By seeking review at this early stage, GEUS wanted to take the opportunity to refine, as appropriate, their approach to reflect international good practice in the field. In turn this would help build stakeholder support for the approach in Denmark.

The review has been carried out by a team of international experts from the organisations responsible for scientific aspects of the geological disposal programmes in Switzerland and the United Kingdom, herein referred to as the "review team". In presenting their findings, the review team has made a number of recommendations for GEUS to consider as they develop the process further.

The review considered the draft criteria report and the review team also held virtual workshops with GEUS, Danish Ministry of Higher Education and Science (MHES), and Danish Decommissioning (DD) on May 17th and 18th, 2021.

The remainder of the review is structured in two main parts. The first considers aspects of the siting process which need to be considered in the geological exercise. The second part focused on the detail of the GEUS proposals as set out in the report.

[1] Hereinafter referred to as "the Report"

2. Siting process

2.1 National context

Denmark has no nuclear power plants but has operated three research reactors at the Risø site which are now being decommissioned. Radioactive waste is in interim storage at Risø, where the storage facilities are being expanded and enhanced to increase capacity and improve robustness against flooding etc.

In line with international best practice, and to meet the requirements of EC Directive 2011/70, Denmark is currently planning for the disposal of Danish radioactive waste. The final disposal solution will need to accommodate up to 10,000m^3 waste with various inventory.

2.2 Policy

The policy position on the long-term management for Denmark's radioactive waste is described in Parliamentary resolution **B 90.** The policy states that the solution must be implemented observing fundamental principles for radiation protection and safety, including protection of people and the environment, protection outside of national borders, and protection for future generations. It also states that the health effects on future generations as a result of the long-term solution must not exceed current acceptable levels in Denmark.

In response to stakeholder comment about previous proposals, the Government defines the long-term management solution could be a deep geological repository and recognises a similar solution to those being implemented in Sweden, Finland and France.

The policy defines a number of requirements for the host rock (bedrock)

- depth of up to 500 metres
- low permeability
- sufficient thickness (more than 100 metres)
- horizontal continuous expanse (several kilometres) across the whole survey area.
- sufficiently homogeneous without physical discontinuities such as fissures and faults.
- as mineralogically homogeneous and uniform as possible.

In addition, the geological conditions must be geologically stable in the short and long term.

The policy also sets out the safety standards and the principal steps in the siting process. The first stage in the siting process will be a review of existing geological information to a depth of 500 metres and that the final localisation should be determined from a precise analysis of a number of criteria; geological, physical and socio-economic. It also states safety will be the most significant component for the selection of the final localisation.

Whilst these clear policy requirements are helpful in providing direction for the programme, by drawing on the solutions adopted in other countries without the underpinning justification, it provides some constraints on the siting process which exclude some potential options.

These points will be considered in more detail in the subsequent sections.

2.3 Roles and responsibilities

An observation of the review team was that, whilst the close cooperation between the organisations involved in waste disposal was apparent, the specific responsibilities of the various actors in the siting process had not been defined. In the past decades, most countries undertaking this important exercise have clearly allocated responsibilities and tasks among the various stakeholders (e.g. authorities, government and ministries, geological service, research institutes, implementer). For the currently very successful process in Switzerland, for example, it was very important for Nagra (as implementer) to concentrate only on the scientific and technical aspects of developing repository concepts suitable for Switzerland, aspects of long-term safety and site selection.

Therefore, the review team recommends that the various responsibilities in the siting process are defined and documented, so that the actors themselves are clear and the approach can be clearly communicated to other stakeholders. The siting process is being led by the Government department MHES who are leading on the engagement process. GEUS are providing technical support. Whilst, geological input is rightly the domain of GEUS, inputs on facility design and safety analysis should be the responsibility of DD. Furthermore responsibility needs assigning for 'other' siting factors e.g. environment, habitats, infrastructure, transport.

2.4 Inventory

The radioactive waste in Denmark stems from the decommissioning of nuclear research facilities at Risø National Laboratory and the use of nuclear radiation sources in research, industrial production and the health sector. It is currently being stored by the Danish Decommissioning (DD) on the Risø peninsula. The majority of the waste is low-level. There is a small amount of used fuel from the DR-1 reactor, for which the government leaves open the option to dispose of in an international repository, if such an option becomes available, but is currently included in the inventory for disposal in Denmark.

The inventory also includes a volume of uranium tailings (NORM waste) which may also be managed separately.

The volume of waste and the associated radioactivity to be managed in Denmark is small. Certainly with the exception of the research reactor fuel, it would be expected that a disposal facility at a depth of 100m or less would provide sufficient isolation and containment for a safety case to be made. The relatively low hazard of the waste and its physical form means that long-lived radionuclides are present in a form which would mean that any long-term release would be controlled by the slow dissolution rate of the waste matrix. Similar near-surface facilities for this type of low-and intermediate level waste have been successfully implemented elsewhere (e.g. the SFR facility at Forsmark in Sweden, which has been operating since the late 1980s, or the Wolseong Low and Intermediate Level Radioactive Waste Disposal Centre (WLDC) at Gyeongju in South Korea, in operation since 2013 etc.).

The chosen depth of disposal is frequently influenced by societal as well as technical factors. The policy document B90 recognises the societal desire for a greater level of isolation from the surface environment for the waste inventory than would be required based on purely technical and safety considerations. The parliamentary resolution B90 records that a facility at a depth of a few tens of metres could potentially satisfy the safety requirements established by regulatory authorities, even when this research reactor fuel was included.

The review team was satisfied that the proposed solution of geological disposal at a depth of a few hundred metres provides a potential solution for the wastes that would meet both technical (safety and engineering) as well as stakeholder needs. However, they recognised the significant cost associated with this disposal solution, particularly given the relatively small volumes and radioactive hazard of the waste inventory. The review team also recognised that much of the drive for facility depth was due to the presence of used fuel in the inventory and that other options for the management of this material were still under consideration. Therefore, it is recommended that the possibility of disposal at shallower depth is not excluded, in the case that an alternative solution for the used reactor fuel could be realised before a final siting decision is made.

2.5 Safety concept and safety analysis

As set out in Policy document B90 and in line with international best practice, a multi-barrier disposal concept is proposed for Danish waste with the main barriers comprising:

– waste containers with waste and filling material

– repository building with waste containers and filling material

– the surrounding geology.

Figure 1 of the GEUS Report illustrates the DGR concept, the emphasis being on the depth. However, no detail is provided on the choice of barrier materials, design features such as vault size and any plans to segregate different waste types, e.g. different types of decommissioning waste or decommissioning waste from spent fuel. This information will be required to inform design requirements such as facility footprint, which in turn will inform geological requirements such as the required rock volume. Given the approach to siting, starting from a 'blank map', the tailoring of safety concepts to different geological settings will also be important.

The review team therefore recommends that preliminary development of the safety concept and facility design for the purposes of supporting the siting process and, in particular any early geological requirements, such as the required volume of potential host rock. These concepts and designs will need to be developed for, or adaptable to, all potential host rock types under consideration in the siting process. The safety concept is also a key input to safety analysis. International experience can be a useful resource in developing these preliminary facility concept designs.

The role of safety analysis in site selection needs to be clearly defined, including the stages at which safety analysis will be considered and the approach and type of output that would be expected. Assumptions may be required, particularly at the early stages when limited data will be available. These assumptions and their rationale would need to be clearly documented. Again, international experience[2] would provide a useful source of data. For a safety analysis to be carried out, the safety-relevant requirements (defined by the regulator), a preliminary disposal concept (based on the

[2] In terms of the practical consideration of safety analysis in evaluating different sites, one example would be the approach proposed by the Swiss regulator (ENSI, 2010: Anforderungen an die provisorischen Sicherheitsanalysen und den sicherheitstechnischen Vergleich - Sachplan geologische Tiefenlager Etappe 2, (In German – informal translation of the title: Requirements on the provisional safety analyses and the safety-based comparison – Sectoral Plan for Deep Geological Repositories Stage 2), ENSI 33/075, Swiss Federal Nuclear Safety Inspectorate, www.ensi.ch

expected waste inventory) and assuming potential host rocks must be available (based on international best practices). These outputs are important, for example, in the evaluation of technical criteria at a site, leading to exclusion or acceptance of a site. In the course of the site selection procedure, it is important to regularly repeat the safety analysis on the basis of new data and findings and to confirm the corresponding safety case.

2.6 Schedule

The timescale proposed in Document B90 indicates that site selection activities will be complete in some six years. This appears to be very optimistic compared to other waste management programmes (e.g. SKB, POSIVA, ANDRA, Nagra) in terms of planned resources (time, costs, available manpower and know-how) and time schedule especially for the site selection activities. The review team recommends a careful consideration on what should be expected to be achievable under the given timescales. In particular with respect to the communication with other stakeholders, the preparatory steps for the communication and the required time, should not be underestimated.

As discussed above, the overall programme planning as presented in B90, the review team also recommend a whole-lifecycle cost analysis based on known facts and concepts (waste inventory, disposal concept, etc.) and considering different scenarios. This cost analysis should be part of a periodic review of the Radiation Waste Management Programme. Examples of this are provided in the advanced programmes as well.

3. Geological studies

3.1 GEUS task

Document B90 sets out the specific task which has been allocated to GEUS:

> *"The Government proposes that studies of Denmark's geology to depths of 500 metres be carried out with the aim of identifying potential locations (= areas) for a deep geological final repository. After which, the final localisation (= site) should be determined from a precise analysis of a number of criteria including geological, physical and socio-economic, with weight given to safety as a significant component for the final localisation."*

The review team considers that the use of the terms locations and localisations in policy is helpful in directing the scope of the task to be undertaken by GEUS. Locations can be considered as siting 'areas' – volumes of the geological environment that are potentially suitable for disposal based on technical and safety criteria. Localisations can be considered as equivalent to 'sites' and are decided based on additional non-geological criteria including physical, environmental and socio-economic factors.

The review team advises that the activity of GEUS in Phase 1 is restricted to recommending underground areas which are potentially suitable for geological disposal. Site selection, which will include wider considerations, should be a separate step in the siting process. The identification of potential areas for a DGR, based on a national geological evaluation ('blank map of Denmark'), can then be used to inform the factors that will be applied to identify specific DGR sites. The UK programme used six such 'siting factors', none of which are specifically geological, but three of which are heavily influenced by geology (safety, engineering feasibility, value for money; see: RWM, 2020).

The review team also noted that siting of surface facilities and associated infrastructure (tunnels, bridges, roads, railway tracks, etc.) is a sensitive aspect of the siting process, as demonstrated in the Swiss programme. It can play an important role in involving other stakeholders in the decision-making process, such as local communities, thereby also increasing the acceptance of the project. This is particularly important as the location of surface facilities and the design and function of these facilities are usually not relevant to the long-term safety of a DGR.

It should be noted that the selection of the location for surface infrastructure can strongly influence the development of a region, e.g. from a socio-economic point of view, or focus on environmentally relevant aspects, such as potential influence on aquifers for drinking water supply or nature conservation areas. Here again it will be important to define the process and the distribution of roles clearly and openly.

In terms of methods of analysis the review team suggests that a qualitative approach may be preferred whilst application of semi-quantitative methods such as multi-attribute decision analysis (MADA) can be problematic, particularly due to the difficulty in defining early on in the siting process the interdependencies and relative weightings of attributes.

3.2 Disposal depth

Document B90 defines 500m as the "target" depth for disposal. In interpreting the policy for the geological exercise, GEUS have defined a depth range for consideration in Phase 1 as 400 – 600m. The review team supports this approach of identifying a range and the depth range selected by GEUS.

However the team notes that, from Phase 2 of the site investigation, the depth of investigations will extend beyond the target depth in order to fully characterise the geology of the underburden.

The review team recommends that some consideration be given to the geological environment at shallower depth. In addition to informing potential groundwater return pathways, safety assessments and engineering feasibility, such information might become more significant if spent fuel can be managed by another route other than disposal in a DGR (see Section 2.4) and an option for a shallower depth repository is considered. The review team recognises that this is beyond the current mandate of GEUS and this point is mentioned here for completeness and consistency with statements in Section 2.4.

3.3 Host rock

At the depth of 500 metres specified in document B90, there are four potential host rocks for geological disposal in Denmark:

- Chalk
- Mudstone
- Granite
- Salt diapirs .

Given the blanket of Chalk that covers much of mainland Denmark to depths in excess of 500m the review team questions whether the target depth would need to be increased if mudstone host rocks are prioritised. In addition, it is not clear if for all host rocks identified above the same disposal concept would be considered (see also remarks in Section 2.5) and hence the same requirements would be valid for the criteria, sub-criteria (and indicators) used. The review team recommends clarifying this point.

3.4 Data sources

The approach presented by GEUS in its Report is primarily based on “hard” data from wells/boreholes and seismic investigation. Understandably it is not expected that the entire Danish territory will be covered by such hard data. The review team would encourage GEUS to use all additional information, for example geological sections in the literature or in university textbooks, information available from private sector (construction companies, geothermal investigations etc.), properties of formations from similar formations in other areas (Denmark or neighbouring countries) etc. It is recognised that there may be large uncertainty associated with such interpolations of data, but at this stage of the screening process, where large areas of 25 km^2 (or more) are sought it is appropriate.

The UK National Geological Screening undertook such an exercise in which public domain data were used to describe, in layperson’s language, the geology of the entire area of England and Wales in terms of its relevance for DGR safety (see RWM, 2016). Providing it is made clear that these descriptions are based on a mostly sparse and sometimes quite old dataset, the UK experience was that this open sharing of available information worked well with stakeholders benefitting from the greater understanding it gave them.

Such a formulation could also be included in Step 1 shown in Figure 4 of the Report.

3.5 Evaluation approach - Criteria and requirements

GEUS has proposed a number of geological criteria in Table 1 of the Report. The review team supports this approach and considers that these criteria and sub-criteria capture the main issues to be evaluated for the geological part of the repository system. The review team noted, however, that these criteria and sub-criteria correspond to a high level of consolidated information. For their evaluation it would be easier to systematically define underpinning information that can be used for their evaluation. A possible term, used in other programmes, for example in Switzerland, could be "indicators", which represent factors that can be evaluated (quantitatively or qualitatively) to assess the degree of suitability of an area or a site with respect to this indicator. An example of indicators is given in the Appendix A.1 (from Zuidema and Vomvoris, 2017).

The review team noted that in the report GEUS has already used such indicators to a certain degree. For example, in: i) Section 4.1.1 under the sub-criterion "Spatial extent" four such indicators are identified, or ii) Section 4.1.2 "Hydraulic barrier effect", also four indicators are identified etc. These indicators should be complemented (if needed) and should be given more "visibility", because at the end the evaluation of a criterion builds on the assessment of each of these indicators.

Associated with the indicators are the requirements that an indicator should fulfill and how these requirements are "mapped" to the traffic light system. An example of such requirements is shown below (from NTB 08-03, unofficial translation) and corresponds to the sub-criterion 1.4 Release Pathways applied for a site evaluated as a potential host for L/ILW repository.

Criterion: Release Pathways	
Indicator	**Requirements for the L/ILW repository**
Type of transport pathways and structure of pore space	*Very favourable:* (equivalent) porous medium *Favourable:* Water flow in discontinuities with restricted channelling and favourable conditions for matrix diffusion *Less favourable*: Water flow in discontinuities with marked channelling and average conditions for matrix diffusion *Unfavourable*: Water flow in discontinuities with marked channelling and unfavourable conditions for matrix diffusion
Transmissivity of preferential release pathways	Minimum requirement: $T \leq 10^{-8}$ m²/s If no empirical values available for transmissivity: average clay content ≥ 25% (for sediments, except evaporites) or geological description of rock units and general experience
	Very favourable: $T \leq 10^{-10}$ m^2/s *Favourable*: $10^{-10} < T \leq 10^{-9}$ m^2/s *Unfavourable to less favourable* (gradual scaling): $10^{-9} < T \leq 10^{-8}$ m^2/s Uncertainty and tectonic overprinting considered in the evaluation
Clay content	Minimum requirement: If no empirical values available for transmissivity (indicator 'Transmissivity of preferential release pathways'): average clay content ≥ 25% (for sediments, except evaporites) or geological description of rock units and general experience
Self-sealing capacity	Self-sealing capacity taking into account the processes to be expected under the in-situ conditions in the underground disposal zone (closing of fractures / discontinuities due to plastic/elastic deformation and swelling and disintegration of the rock matrix): *Very favourable:* Marked self-sealing capacity *Favourable:* Significant self-sealing capacity *Unfavourable to less favourable* (gradual scaling): no or only small self-sealing capacity

Such an approach may facilitate the communication with other stakeholders, for example the regulatory authority or review commissions. An example of such an application in Switzerland is shown in the Appendix, A2. In Appendix A3, a detailed application of the traffic-light system on the criteria and the relevant indicators is show. This application was made by Nagra, as part of Stage 2 of the site selection in Switzerland.

Note, that the intention of the review team is not to recommend that the exact same approach should be followed by GEUS, rather to better illustrate the potential uses of this traffic-light approach in the site selection process in Denmark.

3.6 Criteria- wording

The review team proposes that the wording of a criterion or sub-criterion is such that it identifies the issue to be addressed and evaluated, for example, “spatial extent”, rather than the requirement for that particular issue. The latter should be part of the indicators used and the requirements for each of these indicators. GEUS has used this approach for most of the sub-criteria, with one minor exception, namely, “2.2 Free of erosion” should be rephrased to “Erosion” and then it should be defined for the assessment of this criterion under which conditions a site would be very suitable or suitable etc.

With respect to the sub-criterion 5.1 Conflicts of land/area/subsurface use and its classification under socio-economic conditions the review team would propose to include in the geological criteria a sub-criterion on expected conflicts of use from the geological point of view, for example resources in an area or site being evaluated. The socio-economic aspects include a variety of other criteria that are beyond the scope of “geological” evaluation.

3.7 Narrowing-down process and exclusion criteria

The criteria defined by GEUS could also be used to define exclusion regions. These can be at the large scale, as an example (not an exhaustive list):

- certain respect distance from known regional faults,
- approach to onshore environments
- natural resources – are these areas excluded under future conflict of use, exploitation of future resources
- earthquakes

With respect to earthquakes, the review team notes that this is an example of a criterion that may not help to exclude or distinguish among different areas. However, its inclusion underpins the completeness of the approach proposed by GEUS and that the relevant geological aspects have been considered.

The exclusion criteria and their application in the process, including the requirements that need to be fulfilled for an area not to be excluded, should be defined and should be applied at the initial first stage of the site selection process, i.e. the current Phase 1. It was not clear to the review team if exclusion criteria (with the exception of depth) have been or will be used in the narrowing-down process leading to the definition of suitable areas.

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3.8 On the application of the traffic-light approach

The review team finds the introduction of the traffic light system a very useful tool to help in this screening process. The basis for its application should be the requirements that have been defined for the various criteria/sub-criteria and, if adopted, the indicators and the respective requirements as discussed in Section 3.5. The two examples mentioned in Section 3.5 and shown in the Appendix (A2 and A3) illustrate such applications.

The review team would recommend having a trial run of the traffic light system application to assess if the approach can be applied as is or aspects than can be approved.

4. Concluding remarks

The approach proposed by GEUS contains the required elements for an effective siting programme in Denmark. The review team has identified a number of potential improvements which could increase flexibility and transparency and help optimise the site selection process.

In addition to geological criteria considered in detail here, the review team noted that a number of other aspects would also need to be considered.

Finally, the review team would like to thank our Danish counterparts for their time in effective preparation for the review and their active and constructive participation in all the review meetings and wish them every success in their search for a disposal site.

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Appendix

This Appendix includes more detailed information on references made in the main report.

A1. Criteria and indicators- example

Criteria and indicators used in the site selection process in Switzerland (from Zuidema and Vomvoris, 2017)

TABLE I. Criteria for site evaluation from the viewpoint of safety and engineering feasibility

Criteria group	Criteria
1. Properties of host rock and of surrounding formations contributing to waste isolation	▪ Spatial extent ▪ Hydraulic barrier effectiveness ▪ Geochemical conditions ▪ Release pathways
2. Long-term stability	▪ Geologic / tectonic stability ▪ Erosion ▪ Repository-induced effects ▪ Resource conflicts
3. Reliability of geological information / conclusions	▪ Ability to characterize the host rock ▪ Explorability of the spatial conditions ▪ Predictability of the long-term changes
4. Engineering suitability	▪ Geomechanical properties and conditions ▪ Underground access and management of inflowing water

For the application of the criteria, Nagra has further defined for each criterion corresponding indicators and, for each indicator, the minimum (indispensable) requirements that have to be met as well as, in many cases, more stringent ones, which if they were met would have a further favourable impact on long-term safety and engineering feasibility. Table II summarises these indicators. Note that each indicator is presented only once, even if it was used several times in the narrowing-down process.

TABLE II. List of criteria and corresponding indicators used in the assessment process

Sectoral Plan criteria Indicators used
1.1 Spatial extent
Depth below terrain with respect to engineering feasibility*
Depth below terrain with respect to rock decompaction*
Depth below terrain with respect to erosion*
Depth below rock surface with respect to glacial scouring*
Thickness*
Distance to regional fault zones and to disturbed zones*
Lateral extent
Space available underground*

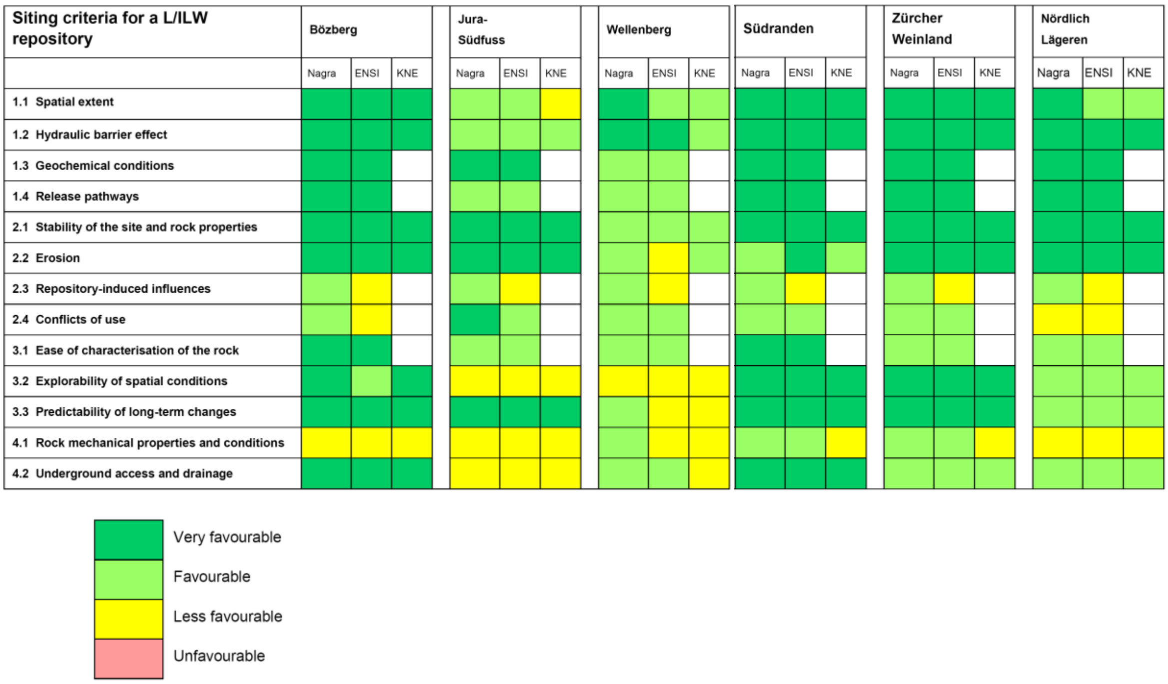
1.2 Hydraulic barrier effect
Hydraulic conductivity*
Groundwater systems
1.3 Geochemical conditions
Mineralogy
pH
Redox conditions
Salinity
Microbial processes
Colloids*
1.4 Release pathways
Type of transport pathways and structure of pore space*
Homogeneity of rock structure*
Length of release pathways*
Transmissivity of preferential release pathways*
Clay content
Self-sealing capacity*
2.1 Stability of site and rock properties
Conceptual models of geodynamics, tectonics, other processes*
Seismicity*
Conceptual models of geochemical processes
Rare geological events (volcanism)
Potential for formation of new water flowpaths (karstification)*
2.2 Erosion
Large-scale erosion over the time period being considered*
2.3 Repository-induced effects
Excavation damaged zone adjacent to underground structures
Chemical interactions
Host rock behaviour with respect to gas
Host rock behaviour with respect to temperature
2.4 Resource conflicts
Natural resources within the host rock
Natural resources beneath the host rock
Natural resources above the host rock
Mineral and thermal springs
Geothermal resources
3.1 Ease of rock characterisation
Disturbed zones
Variability of rock properties with respect to ease of characterisation*
Experience
3.2 Explorability of spatial conditions
Regional fault pattern and bedding conditions
Continuity of strata of interest
Exploration conditions underground*
Exploration conditions at the surface
3.3 Predictability of long-term changes
Tectonic regime (zones to be avoided conceptually)*
Independent evidence of long-term isolation
4.1 Rock mechanical properties and conditions
Rock strengths and deformation properties
4.2 Underground access and drainage
Geotechnical and hydrogeological conditions in overlying rock formations*
Natural gas transport (in host rock)

*: indicators of special importance to safety and engineering feasibility for the host rocks and siting regions chosen in Stage 1. These indicators play an important role in the narrowing-down process in Stage 2.

A2. Application of the criteria by different stakeholders – example

An example of the application of the criteria and the use of the traffic-light system by different stakeholders is shown in the figure below. The example is from the Swiss site selection process (siting regions, equivalent to "areas" in the Danish approach).

Nagra, ENSI (Swiss regulator) and KNE (Commission on Nuclear Waste Disposal) evaluation of the siting regions proposed by Nagra for the L/ILW geological repository. The evaluation is shown against the safety and technical criteria in the Sectoral Plan (from Ernst et al, 2010).



A3. Application of the traffic-light system at the indicator level – example

The example here shows the application of the traffic-light system at the level of the relevant indicators in the site selection in Switzerland at Stage 2 (narrowing down to at least two sites.

The figure below shows the safety-based evaluation of the siting regions according to the criteria and decision-relevant features and indicators (Zuidema and Vomvoris 2017, Fig 4).