DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/46

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report no. 6

Characterization and description of areas Sjælland

Peter Gravesen, Bertel Nilsson,
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1. Introduction

The low and intermediate level radioactive waste from Risø: the nuclear reactor buildings, different types of material from the research periods and waste from hospitals and research institutes have to be stored in a final disposal in Denmark for at least 300 years (Indenrigs- og Sundhedsministeriet, 2005, 2007). The task is to locate and recognize sediments or rocks with low permeability which can isolate the radioactive waste from the surrounding deposits, the groundwater resources, the recipients and from human activities. The sediments or rocks shall also act as a protection if the waste disposal leaks radioactive material to the surroundings. This goal can be reached by low water flow possibilities, strong sorption capacity for many radionuclides and self-sealing properties.

The investigation of geological deposits as potential waste disposals for high radioactive waste from nuclear power plants has earlier focused on deep seated salt deposits and basement rocks. Nevertheless, the Tertiary clays were mapped as well (Atomenergikommissionen, 1976, Dinesen, Michelsen & Lieberkind, 1977). The salt diapirs and the salt deposits are not included in the present study.

The task is to find approximately 20 areas potentially useful for a waste disposal. The 20 areas have to be reduced to 1-3 most potential locations where detailed field investigations of the geological, hydrogeological - hydrochemical and geotechnical conditions will be performed.

2. Background

In Denmark many different fine grained sediments and crystalline rocks occur from the earth surface down to 300 m depth. Therefore, the possible geological situations include sediments and rocks of different composition and age. These situations are also geographical distributed over large areas of Denmark. These sediments and rocks are shortly described based on existing information in Report no. 2, where five different types are included. 1: Crystalline granites and gneisses of Bornholm (because these rock types are host for waste disposals in many other countries). 2: Sandstones and shales from Bornholm (as these sediments are relatively homogenous although they have fracture permeability). 3: Chalk and limestone (because these sediments may act as low permeable seals, but in most areas act as groundwater reservoirs). 4: Fine-grained Tertiary clay deposits (as these sediments have a low permeability, are widely distributed, and can reach large thicknesses). 5: Fine-grained Quaternary clays from Elsterian, Saalian, Weichselian and Holocene. These sediments are distributed all over Denmark.

The geological formations most studied in Europe for disposal of radioactive waste are clay (in Belgium, France, Germany and Switzerland), crystalline rocks (Sweden, Finland and Switzerland) and salt (Germany).

All Danish sand and gravel deposits are excluded from the description owing to their potential as groundwater reservoirs, their high permeability, low sorption capacity and no-sealing properties for the waste. The sand and gravel deposits often occur below or above the low permeable and fractured deposits and sand layers may be intercalated in them.

3. Data and methods

A report from 2007 (Indenrigs- og Sundhedsministeriet, 2007) recommends the types of existing data needed for the preliminary selection of disposal sites. The recommendations are based on guidelines from the International Atomic Energy Agency (IAEA, 1994, 1999, 2005).

Gravesen et al. (2010, Report no. 1) briefly describes the existing data collections including databases, maps and models, which have been used during the work of selections of approximately 20 potentially suitable areas. Most of the information is stored in GEUS databases: Borehole data and co-ordinates, groundwater and geochemical information, GIS based maps, geophysics and much more, but information is also collected from other institutions. The methods are described in more details and the description is the directly background for the selection of the sites.

4. Selection of areas

Selection of potential areas on Sjælland has to fulfil the criteria and answer the questions described and put forwards in Gravesen et al., (2010).

The areas chosen on Sjælland only include Quaternary and Palaeogene deposits on the central, eastern and western parts of Sjælland. At present, the radioactive waste and the buildings are located at Risø. Therefore, an evaluation of this area is necessary. On the eastern part of the Stevns peninsula, tunnels in the Danian limestone are found and storing of the waste in tunnels could be a possibility.

Therefore, it is relevant to investigate and analyse these two different geological situations in relation to potential disposal areas.

5. Area 5. Risø, Middle Sjælland

5.1 The location of the area

The area is located north of Roskilde, central part of Sjælland (Fig. 1).
The area of Research Centre Risø, Danish Technical University (DTU) and the nearby areas are seen on Fig. 2. The RC Risø area has a size of 2.4 km^2. The area is situated by Roskilde Fjord, c. 2.5 km north of Roskilde on both sides of the road Frederiksborgvej 399.
The research centre (at present storing the radioactive waste and the Reactor 3) will be dismantled during the next years.

Figure 1. Location of the area. Risø is located on the central part of Sjælland. East Denmark.

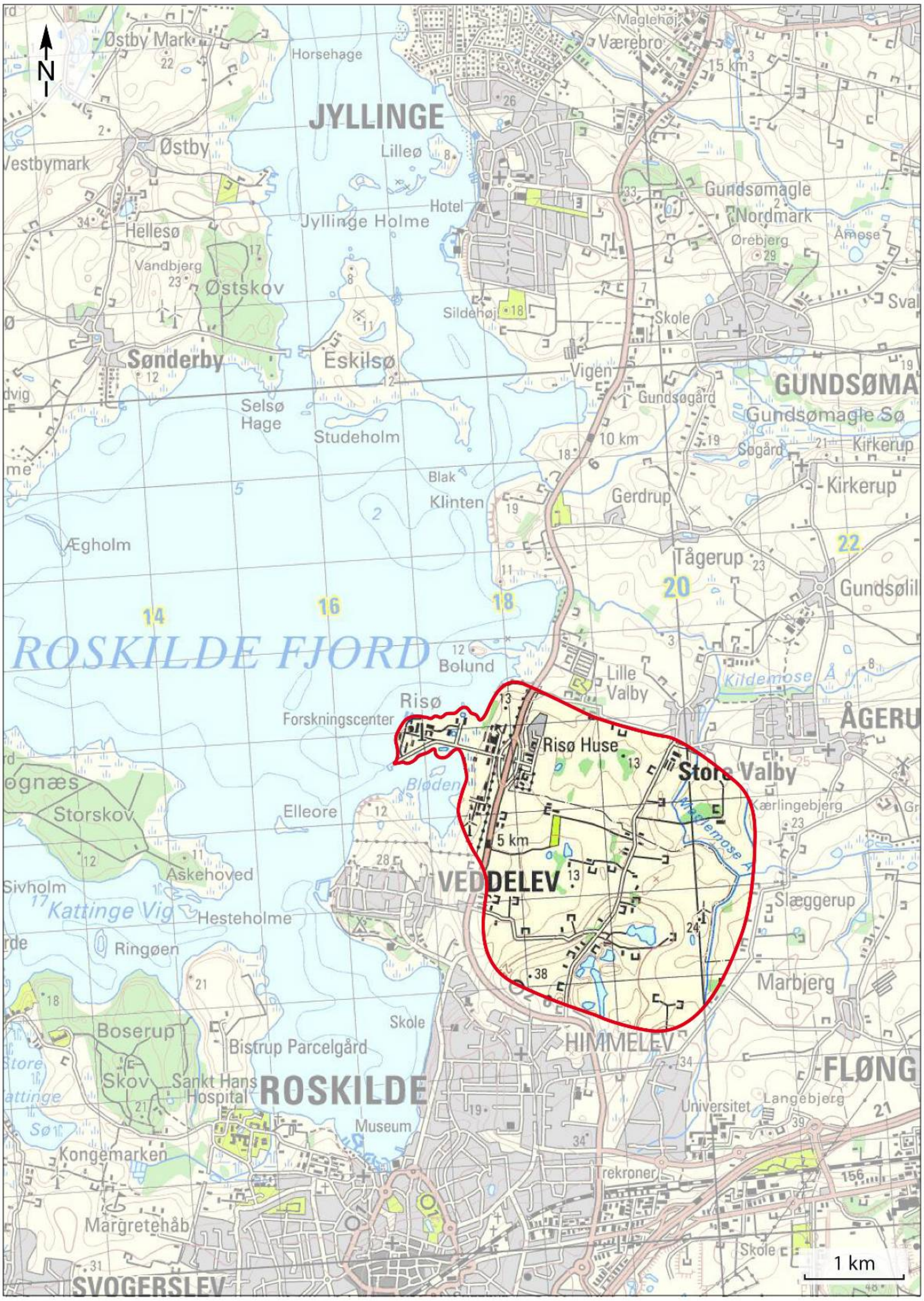

Figure 2. A detailed map of Area 5. Area 5 is located north of the city of Roskilde, by Roskilde Fjord, on both sides of the Frederiksborgvej.

5.2 Terrain, topography and surface processes

The area is located along and next to the eastern coast of Roskilde Fjord (Figs. 2 and 3). The size of the area is c. 10 km^2. The terrain can be separated into three subareas: The peninsula, the coastal area, and the land area. A terrain model for Area and the surroundings can be seen in Fig. 4.

The main part of the peninsula is low-laying, between 0 m and 3.5 m meters above sea level (m.a.s.). A higher area is located at the distal part of the peninsula towards the west and reaches a level of 8.5 m.a.s. On the western part of the peninsula, a shallow coastal cliff can be followed over approx. 200 m. This coastal stretch is protected by stones and the cliff is partly overgrown. The research centre Risø is located on the peninsula. The centre, including buildings, smaller roads etc. make up a larger part of the peninsula.

The coastal area southeast of the peninsula is a narrow, low-lying beach meadow area (Fig. 3) and northeast of the peninsula, the coast is marked by few beach ridges in front of a narrow wood along the coast.

The main road Frederiksborgvej, a windmill and the Risø Huse buildings occupy the western part of the land area. The remaining, a bar far the major part of the area is used for agriculture with scattered houses and crossed by several smaller roads. The land area is a continuation of the coast area and reaches an elevation of + 24 m towards the east and + 38 m towards southwest. Several smaller low-laying lake and moor areas occur and the stream Maglemose Å crosses the eastern part of the area.

Owing to the intensive cultivation, the surface processes (soil creep, frost – thaw processes, soil development etc.) proceed slowly and undramatic. The by far most dynamic processes are found in the coastal zone, but here, the most exposed part of the cliff is protected by stones and the beach meadow is located in a sheltered, shallow cove.

Figure 3. The Risø area: a look towards Reactor 3 and Roskilde Fjord.

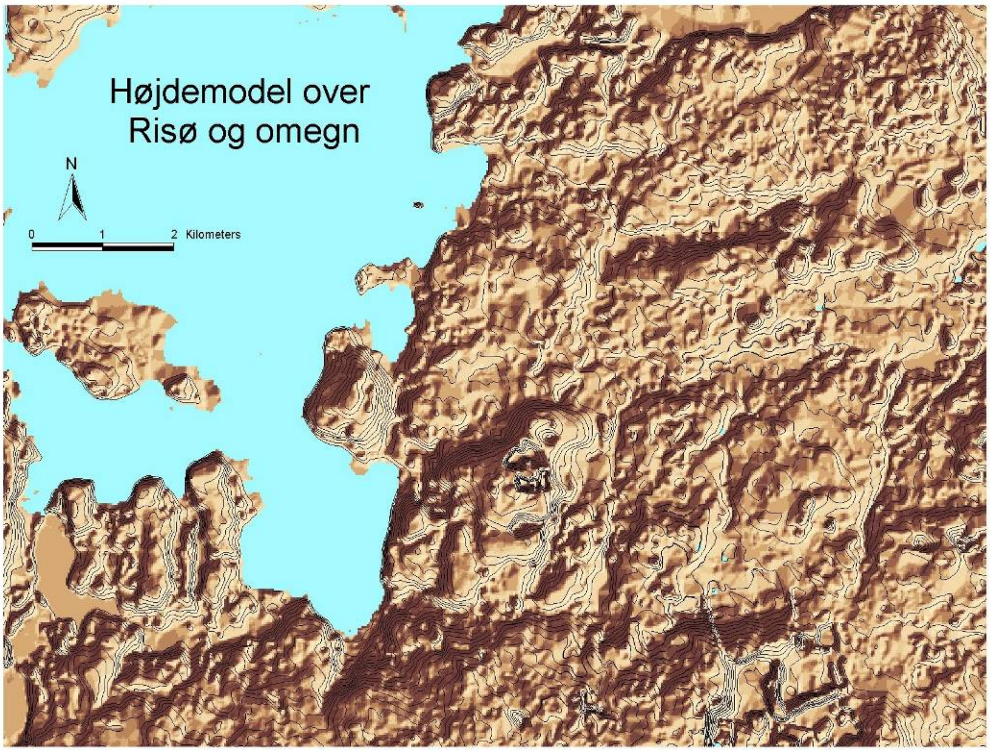

Figure 4. Terrain model of the Risø area and surrounding areas.

5.3 Surface geology and profiles

The surface geology is dominated by Weichselian clayey till deposits with some smaller areas of meltwater sand and gravel. In the low laying areas, Holocene freshwater deposits occur and Holocene marine deposits are found alongshore (Fig. 5).

On the peninsula towards the west a shallow coastal cliff can be followed over approx. 200 m. A 2-3 m thick profile of clayey till is exposed, but now the cliff is protected by stones and the cliff is partly overgrown by plants. On the nearby west side of Veddelev peninsula, the clayey till is also exposed in the cliff.

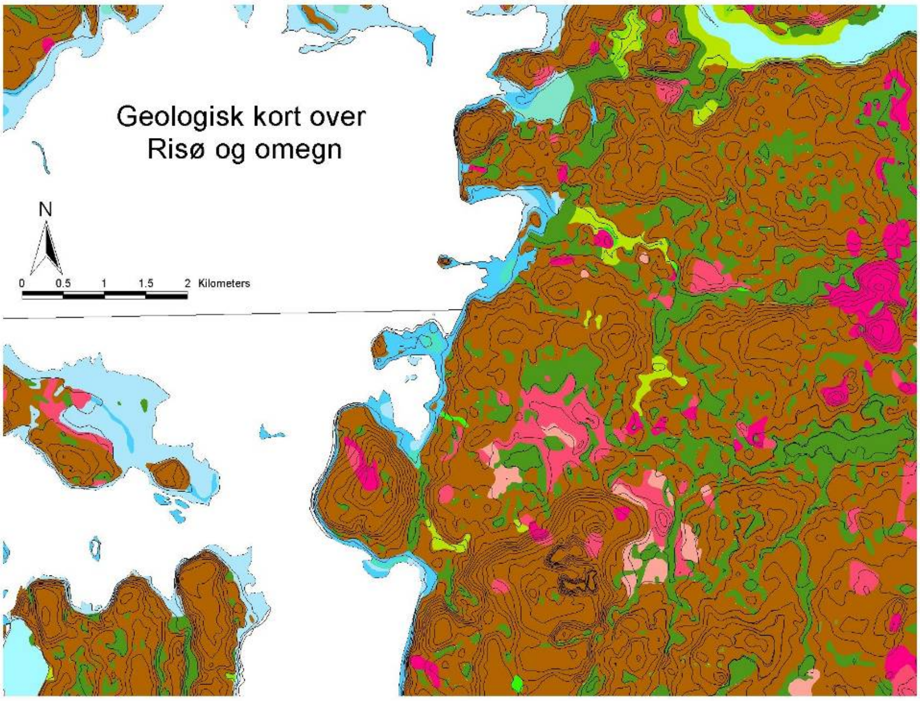

Figure 5. Map of the Quaternary deposits. Scale: Original 1. 100.000. Legend: Brown: Clayey till, red: meltwater sand and gravel, light red: meltwater clay and silt, blue: Holocene marine deposits, Green: Holocene freshwater deposits (After Rørdam, 1899).

5.4 Boreholes

The Well Data Archive at GEUS contains approx.170 boreholes drilled within the Risø area and the near surroundings. Most of the boreholes are drilled on the Risø peninsula and the area east of this area. Only a few boreholes are drilled in the rest of the area.

Most the boreholes are drilled for geotechnical purposes (2-3 m deep) during the years 1950-1960 when the buildings in the area were build. These are not general encoded into the Jupiter Database. This is why they cannot be found on the map Fig. 6 but on an additional map (Fig. 7). The main part of the boreholes on the map (Fig. 6) is water supply wells, which supply small water works and single house-holds, smaller farms and other local needs. Many wells are shallow but because of the need for the optimal water supply the wells have to reach groundwater filled fractures in the pre-Quaternary deposits. Some wells are as deep as 75 m (Fig. 8).

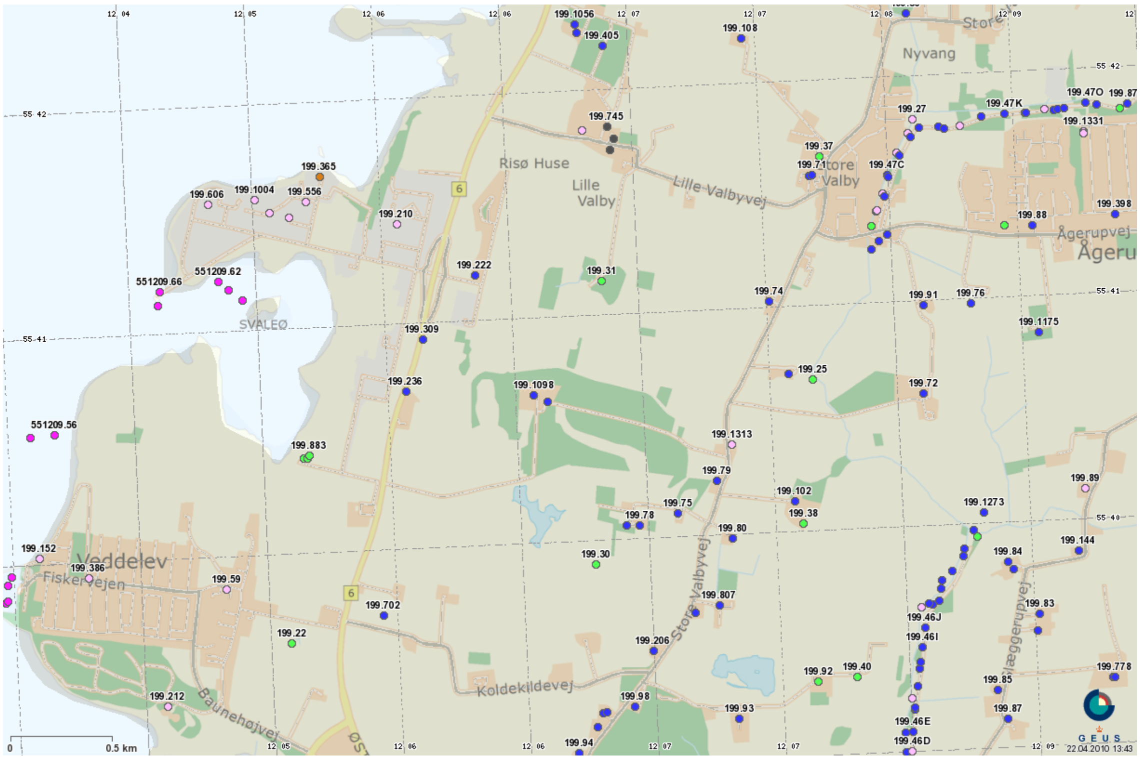

Figure 6. Map of the locations of boreholes from the Jupiter Database at GEUS. Legend: 199.222: DGU no., Blue dot: Water supply well, Red dot: Geotechnical borehole, Pink dot: Raw material borehole, Green dot: Other borehole, Light red dot: Abandoned borehole, Black dot: Unknown purpose.

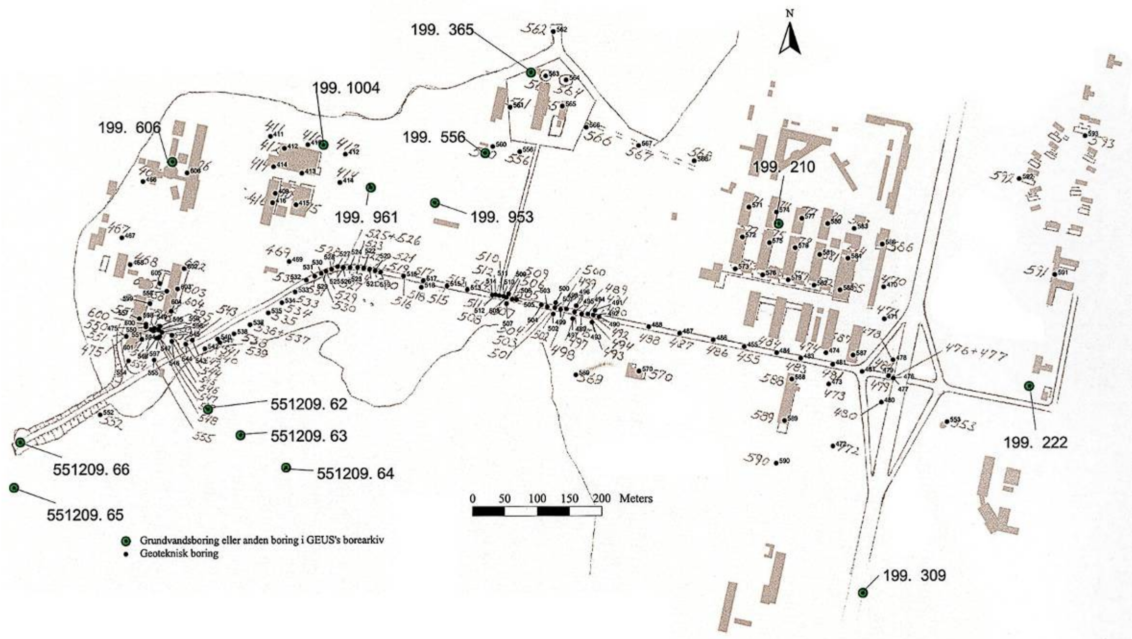

Figure 7. Map showing the location of boreholes on the Risø area (From Gravesen & Pedersen, 2005).

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BORERAPPORT   **DGU arkivnr: 199. 222**

Boreested : RISØ A E K BOR 2 4000 Roskilde	**Kommune** : Roskilde **Region** : Sjælland

Boringsdato : 1/10 1956	**Boringsdybde** : 41.3 meter	**Terrænkote** : 18 meter o. DNN

Brøndborer : **MOB-nr** : **BB-journr** : **BB-bornr** :	**Prøver** **- modtaget** : **- beskrevet** : **af** : G **- antal gemt** :

Formål : Vandforsyningsboring **Anvendelse** : Vandforsyningsboring **Boremetode** :	**Kortblad** : 1513 IVSØ **UTM-zone** : 32 **UTM-koord.** : 695378, 6176384	**Datum** : ED50 **Koordinatkilde** : **Koordinatmetode** : Dig. på koor.bord

		Ro-vandstand	**Pejledato**	**Ydelse**	**Sænkning**	**Pumpetid**
Indtag 1	(seneste)	16.4 meter u.t.	6/3 1978	8.5 m³/t	0.3 meter	
	(første)	13.4 meter u.t.	20/10 1956			

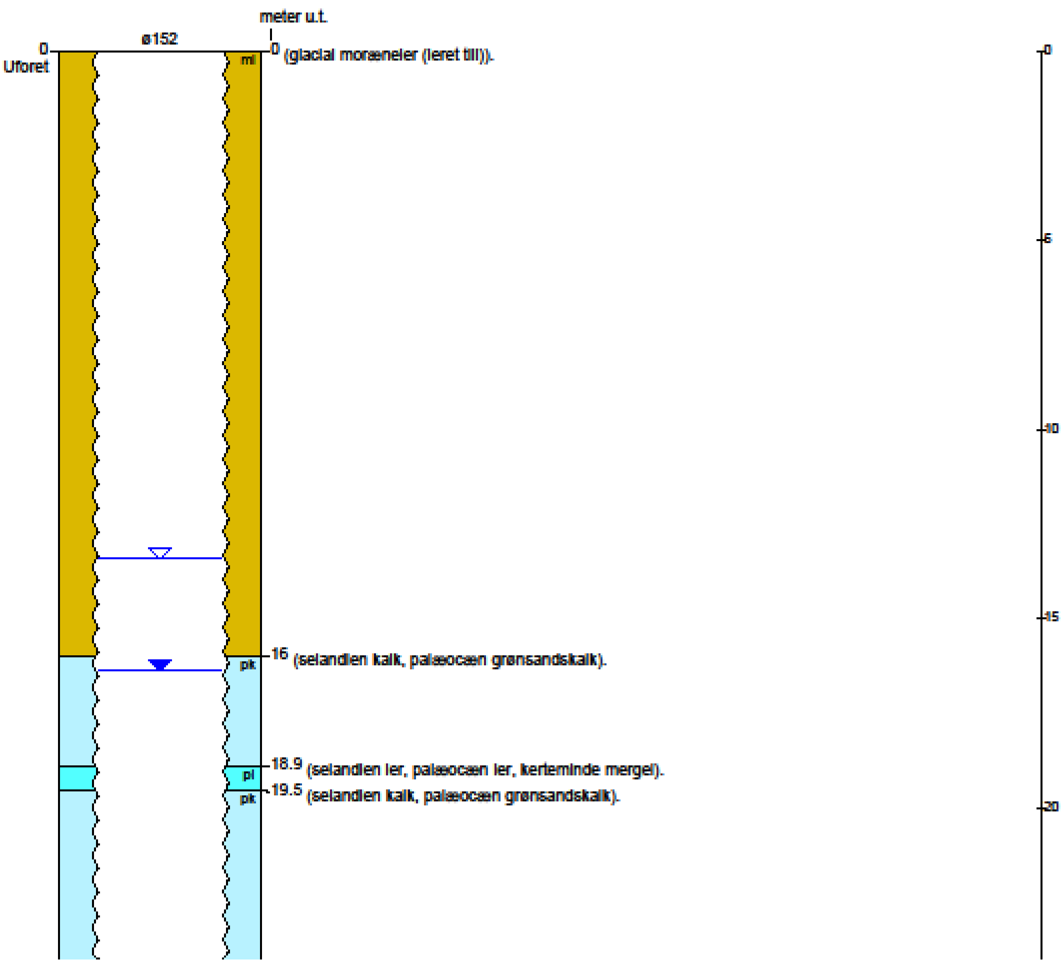

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Figure 8. Geological log from borehole DGU No.199.222. Upper part of the 41.3 m deep borehole. Legend: ML. Clayey till, PK: Paleocene limestone, PL: Paleocene clay.

5.5 Sediment and rock characteristics, mineralogy and chemistry

The Danian, Selandian (Paleocene) and Quaternary deposits found in the area are described mainly based on borehole samples.

5.5.1 Pre-Quaternary deposits

The distributions of the Danian and Selandian deposits from the Paleocene can be seen on Figs. 9 and 13.

Danian

The oldest deposits in the area are from the Danian (61-65 million years old). The deposits are all of marine origin and comprise several white and light grey limestone types with content of chert (flint). A calcarenitic type (kalksandskalk) is often a hard, tight cemented type which can be rich in grey and brown grey flint. The calcisiltitic type (Slamkalk) is soft and contains fine-grained limestone mud with grey flint. The Bryozoan limestone is a loose to slightly cemented, soft limestone with some lime mud and often many bryozoans (colony building animals) together with grey flint. The limestone deposits are often very good groundwater reservoirs with high water yields.

The Danian limestone is at least 35 m thick but the lower boundary is not known.

Selandian

The younger deposits from the Selandian (58-61 million years old) are also marine deposits. In some parts of the area the Selandian deposits are resting on Danian. Two sediment types dominate. Olive grey fine-grained clay (Palæocent ler) with silt strikes and high content of calcium carbonate contains several re-sedimented limestone fragments. The other type is a rather hard, clayey and silty limestone (grønsandskalk) with several animal fossils. Both types contain the marine formed green mineral glauconite often in large amounts. The deposits are good yielding groundwater reservoirs in many areas. Within the area, the occurrences of the Selandian deposits are very variable probably caused by tectonic activity and erosion. In the smaller Risø area, the deposits are 2-6 m thick or absent. Towards the south and below the land area, the layers can increase to 15-30 m but in some parts of the area the deposits are absent. Outside the area, the deposits can reach relatively large thicknesses and the two sediment types can intercalate.

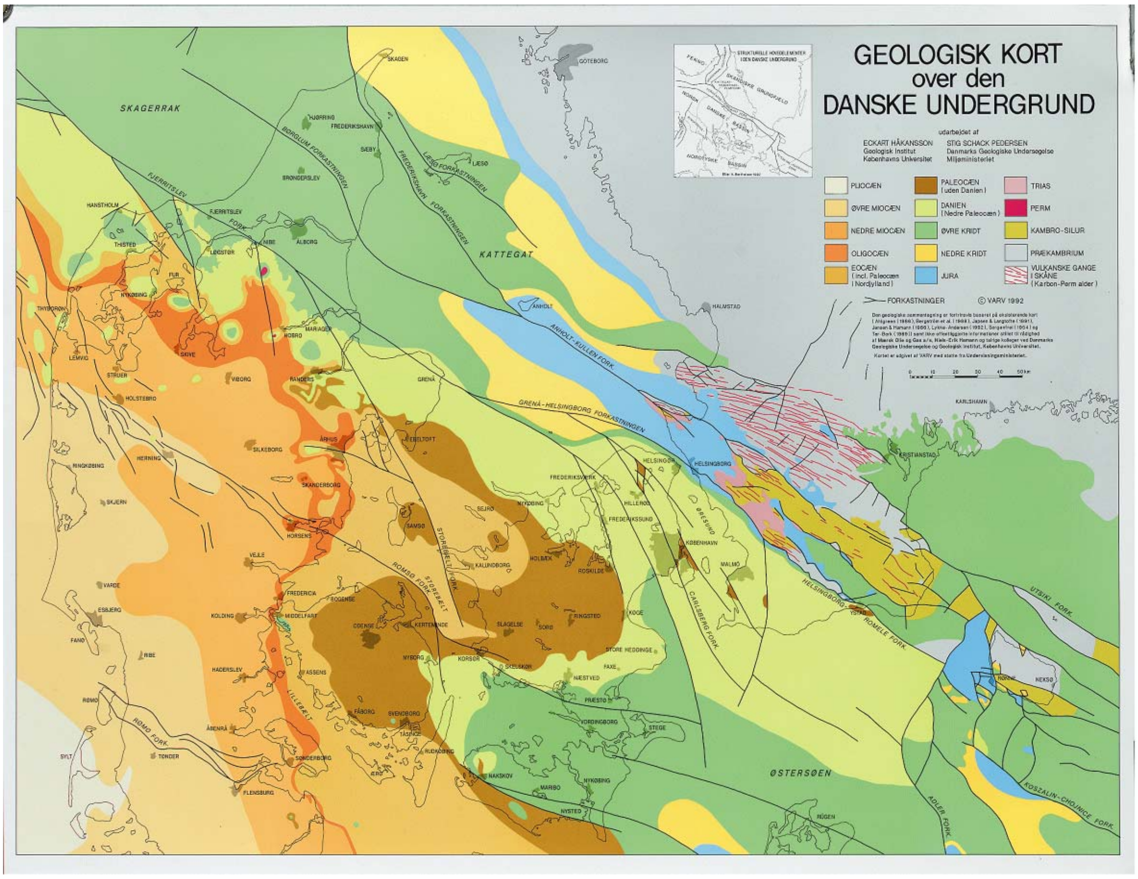


Figure 9. Map of the pre-Quaternary surface: Time units. Original scale: 1:50.000. Legend: Red lines: Precambrian intrusions, grey: Precambrian, olive: Cambrian-Silurian, red: Permian, light red: Triassic, blue: Jurassic, yellow: Lower Cretaceous, green: Upper Cretaceous, light green: Danian, brown: Paleocene, yellow olive: Eocene, red brown: Oligocene, light yellow brown: Lower Miocene, very light yellow brown: Upper Miocene, white: Pliocene (Håkansson & Pedersen, 1992).

5.5.2 Quaternary deposits

The thickness of the Quaternary deposits is changing from approx. 45 m at the peninsula to 10-25 m towards the east and north. All the deposits are assumed to be from the last glacial, the Weichselian 117.000 to 11.500 years ago and from the Holocene (up to recent). The map of the Quaternary deposits of Denmark is seen in Fig. 10.

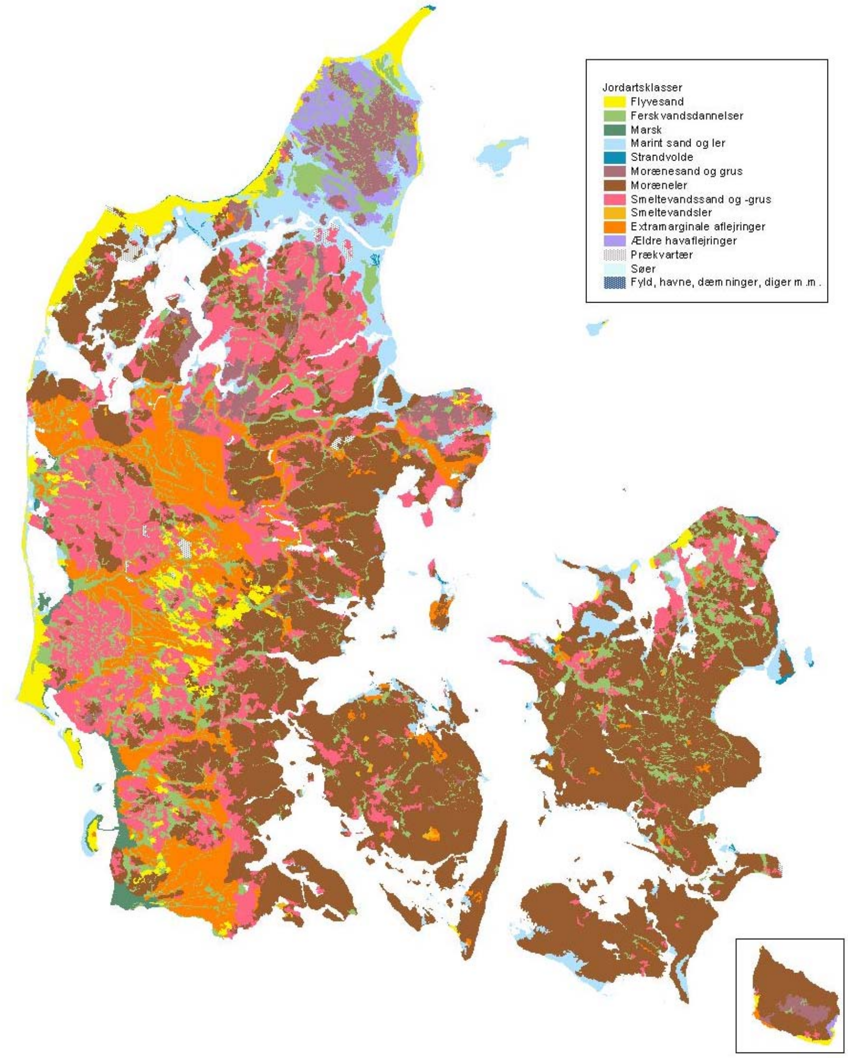


Figure 10. The map of the Quaternary surface deposits. Original scale: 1:200.000. Legend: Brown: Clayey till, light brown: Sandy till, red: meltwater sand and gravel, orange: sandur sand and gravel, purple: Late glacial marine deposits, light blue: Holocene marine deposits. Green: Holocene freshwater deposits, yellow: Aeolian sand (From Pedersen, 1989).

Glacial deposits

The following sequence is found on the peninsula, towards the west:

Below the thin brown topsoil, the upper glacial deposits consist of silty, sandy, brown grey and olive gray clayey till with a varying content of gravel and stones. Just below the surface, the till is yellow or brown because of oxidation. The till is always calcareous in matrix and in particles. The till is cut by vertical fractures and roots. In the cliff section, it can be seen that the upper 2-3 m are penetrated. The clayey till seems very homogenous in the total section although till sediments are regarded as heterogeneous sediment (Figs. 11 and 12). The thickness of the upper till is between 5 and 10 m.

Meltwater deposits are found below the till. These deposits are relatively thick layers of silty or fine-grained calcareous olive gray meltwater clay sometimes intercalating with meltwater silt and fine-grained meltwater sand. The thickness can be up to 20 m. Brown grey calcareous meltwater sand and gravel occur in 8 m thick layers.

The bottom layers consist of silty, sandy calcareous olive grey clayey till with gravel and stones and thin intercalations of sandy and gravelly tills. The thickness can reach 10 to 15 m. More meltwater sand and gravel can occur below these till deposits.

Figure 11. Yellow brown clayey till section from the Weichselian Young Baltic Advance, Risø peninsula cliff.

The following deposits are found along the coast towards the south:
In the area along the coast, the Quaternary deposits can be approx. 20 m thick and consist of the same units as on the peninsula. The lower clayey till can contain large amounts of calcareous material (kalkmoræne). The thicknesses of the three units are: Upper till: 5-8 m, meltwater deposits: 2-7 m and lower till: 5-8 m.

Figure 12. The upper yellow brown clayey till with gravel and stones from the Risø peninsula cliff.

Towards the east on the land area is found:
On the land, from the coast to the east, the upper clayey till dominates with thicknesses of 10 to 20 m. There are thin intercalations of meltwater deposits particularly in the lower part above or at the boundary to the pre-Quaternary deposits.

Holocene deposits

The uppermost layers, found as a rim around the peninsula and along the coast, are from Holocene starting from 11.550 years ago. The boreholes show up to 4 m thick freshwater sediments in level between -4 and -7 m deposited in the low-lying areas in the till terrain. These sediments are deposited in lakes and swamps and consist of peat, gyttja, plant material, sand and calcareous gyttja with freshwater shells.

Above the freshwater sediments follows marine sediments as gyttja, clay, sand and gravel often with marine shells. The deposits can be up to 7 m thick but are often only a few m. They can occur up to level + 3.5 m. Kitchen middens from the Stone Age are found in the marine sediments at foot of the steep slope towards the land area.

5.6 Tectonics, structures and seismic activity

5.6.1 Major tectonic structures

Isostatic uplift after the Weichselian

After melting of the large glacier at the termination of last ice age, the Weichselian, a huge relief of the pressure on the land area happened in the Danish area. This was followed by an isostatic rise of the land area which was most pronounced in the northern part of Denmark. During the following 14.000 years after the rise started a change between isostatic land rise and eustatic sea level rise occurred which have influence on the present distribution between land and sea. This has determined the types of sediments which have been deposited during the time.

Structures at the boundary between the Quaternary and the pre-Quaternary

The boundary between the Quaternary deposits and the older pre-Quaternary deposits is called the pre-Quaternary surface. To show the position of the pre-Quaternary surface five geological sections are constructed based on boreholes data from the area. The sections show that the pre-Quaternary geological layers have been moved along fault lines (Figs. 18, 19, 20, 21). The combination of the geological sections and the pre-Quaternary surface map (Fig. 9) show that fault lines crosses the surface and that the Roskilde fault line is not a local structure but part of some regional structures running north-south through the area. A new map of the surface with a series of three fault lines at the southern part of Roskilde Fjord is prepared and shown in Fig. 13. The description of the tectonic system is found in relation to the regional model in chapter 5.6.3.

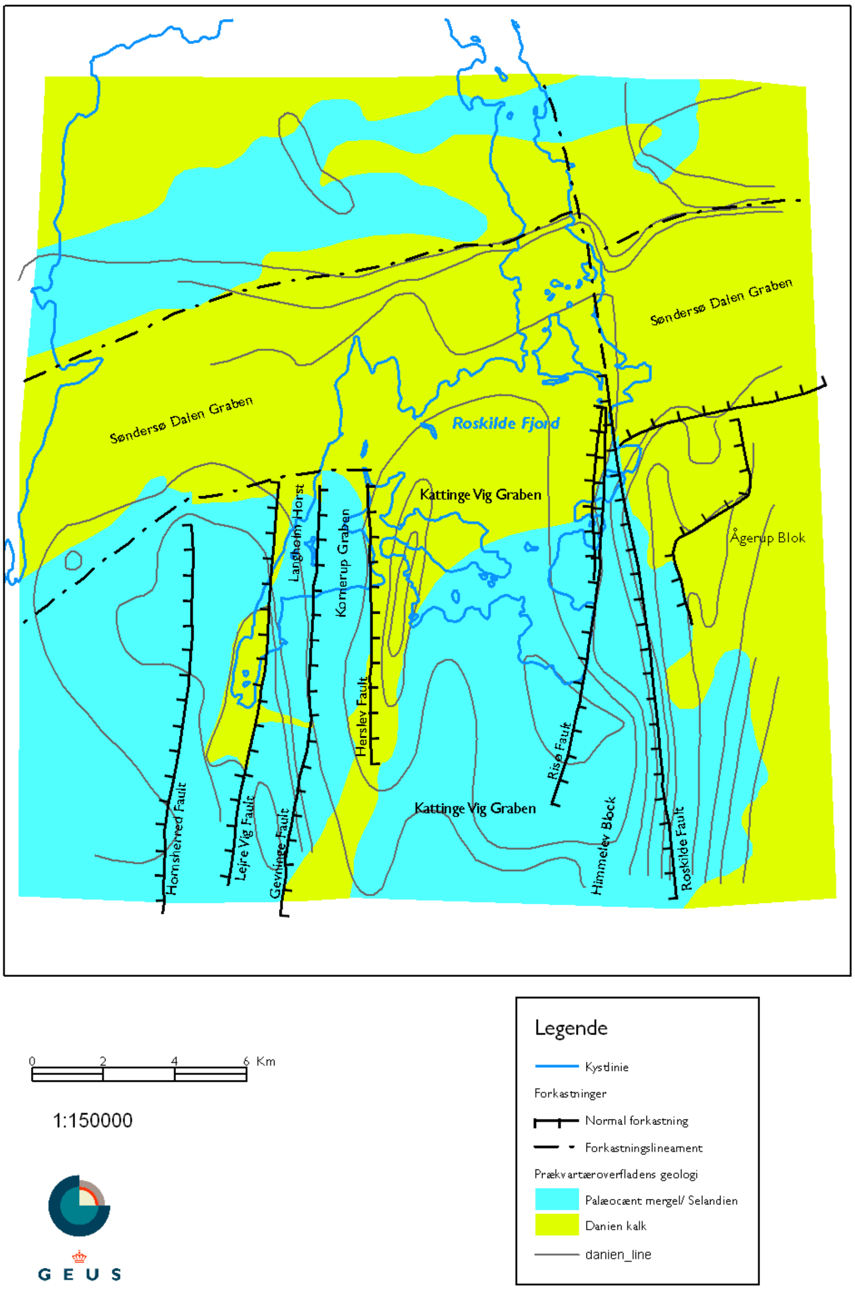


Figure 13. Map of the pre-Quaternary deposits from a larger area around Roskilde and Risø. Legend: Green: Danian limestone, Green blue: Selandian Marl (From Gravesen & Pedersen, 2005).

Deep tectonic features

The deep seated geological layers are mainly described from seismic investigations and few boreholes (from oil-gas surveys) which are combined and interpreted. The mapping of the deeper structures demonstrates a north-south oriented fault zone from southern Sjælland to Risø situated close to the Roskilde fault.

Recently measured movements and neotectonic movements

Measurements of the land level changes show that land level raise of approx. 0.35 to 0.40 mm per year is found in the area at Risø (KMS). These minor movements can be related to slow movement along faults in the underground. The processes are complicated and unpredictable in the interplay between the Danish Basin and the Fenno-Scandian Border Zone where horizontal as well as vertical movements can occur.

Movements that still happen in the Danish area, especially cutting the Quaternary deposits are called neotectonic. Recent disturbances in the Quaternary deposits are very difficult to prove.

5.6.2 Fractures

Vertical and horizontal fractures are known in the Danian and Selandian limestones. These have large importance as the primary permeability is low to medium. The fractures give the sediments a larger secondary permeability which is the basis for the groundwater abstraction. In the clayey tills fractures and biopores are widely distributed mainly in the upper 3-5 m. The three types of sediments are then double porosity media with possible water transport in both micropores and macropores.

5.6.3 Geological and structural models

Geological models

Geological conditions in the area are described in two models in different scales: A very local model (model A) for the proper Risø area only concerning the Quaternary deposits down to 20-30 meters depth and the upper Paleocene layers (Figs. 14, 15, 16 and 17) and larger regional model (model B) covering deposits down to 75 meters depth below earth surface showing the structural conditions (Figs 18, 19, 20, 21, 22, 23).

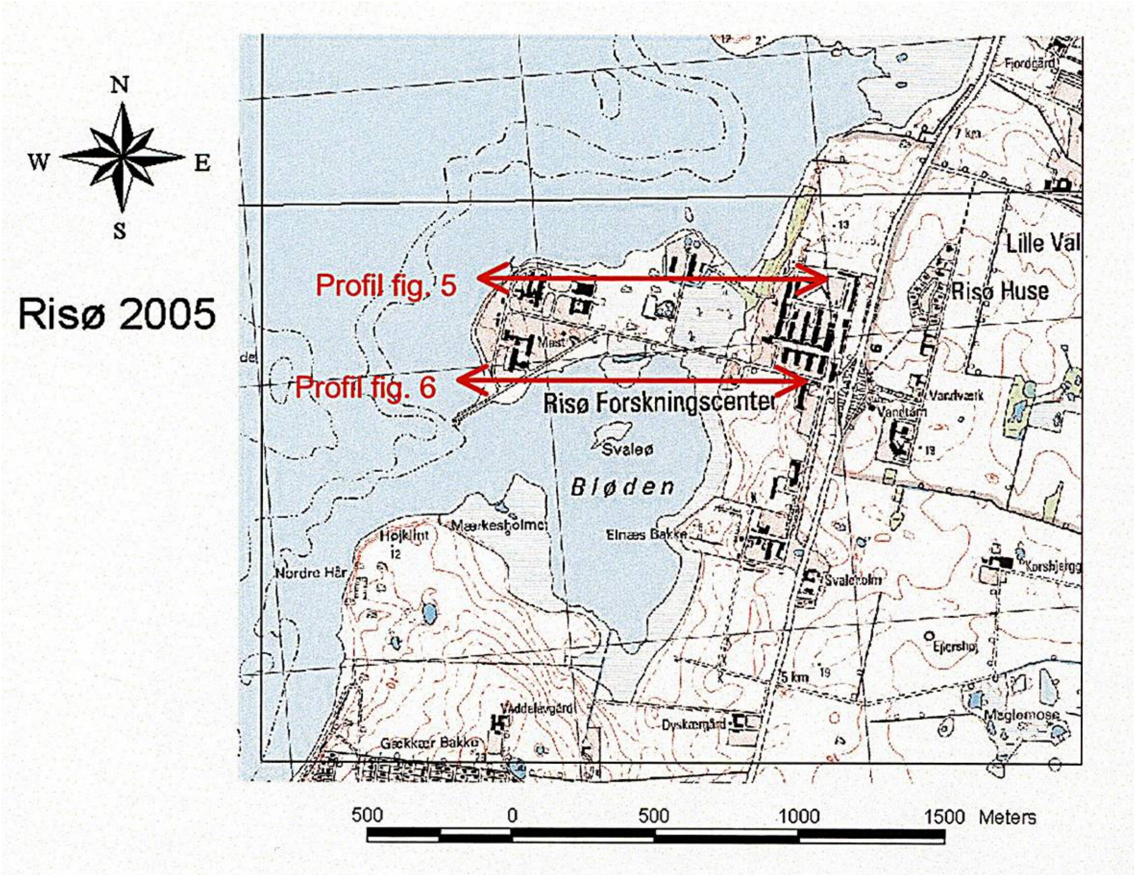


Figure 14. Location of the sections, model A. The section in Fig. 15 is located in Profil Fig. 5 and the section in Fig. 16 is located in Profile Fig. 6 (From Gravesen & Pedersen, 2005).

Model A. Local model: The Quaternary deposits and upper Paleocene deposits

Model A shows details concerning the upper parts of the Quaternary layer´s composition and structures. This is demonstrated in two west-east oriented geological sections situated on the peninsula and the near shore areas (Figs. 14, 15, 16).

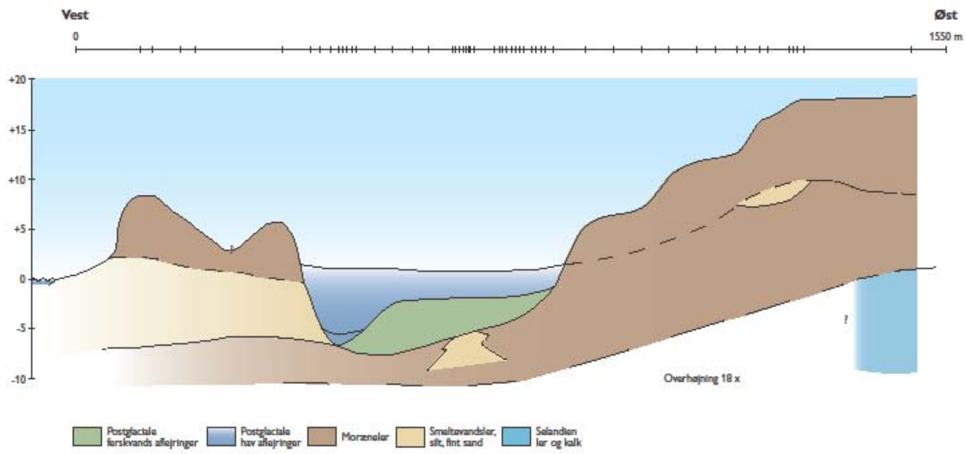


Figure 15. Section from west to east through the southern part the peninsula and the near shore. (From Gravesen & Pedersen, 2005). Legend: Brown: Clayey till, Yellow: meltwater clay, silt, fine sand, Green: Holocene freshwater deposits, Dark blue: Holocene marine deposits, Blue: Selandian clay and limestone.

Above level + 3.5 m the upper clayey till dominates from the ground surface and down to 15 m depth and this clayey till is distributed over nearly the whole area lying below the Holocene deposits.

Below the upper clayey till, meltwater clay, silt and fine-grained sand in thin intercalated layers occur but also isolated layers of coarse-grained meltwater sand and gravel are present.

Below these layers, lower clayey till follows. In places, this till is found directly under the upper till. All the sediments are from the Weichselian, deposited from glaciers or from the meltwater flowing from the glacier. The deposits have been loaded from and crossed by the glaciers and are therefore consolidated.

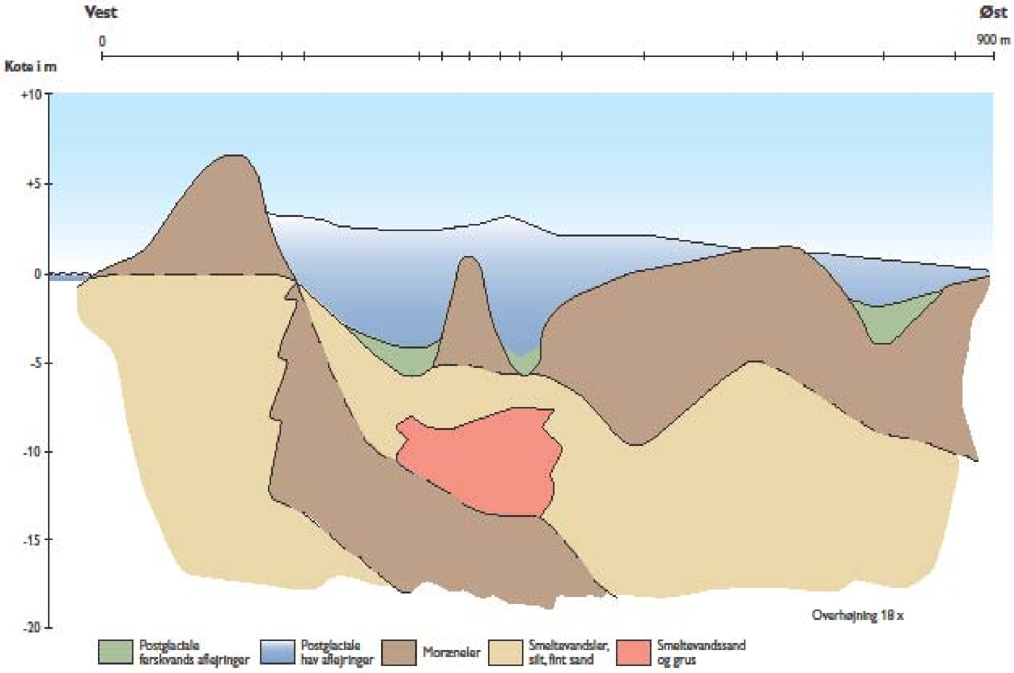


Figure 16. Section from west to east through the northern part of the peninsula and the near shore area (From Gravesen & Pedersen, 2005). Legend: Brown: Clayey till, Yellow: meltwater clay, silt, fine sand, Red: meltwater coarse-grained sand and gravel, Green: Holocene freshwater deposits, Dark blue: Holocene marine deposits.

On the peninsula, the distribution of the Holocene sediments formed in freshwater or in the sea shown that the deposition occurred in a landscape with relief which was composed of clayey till or meltwater sediments. The moraine terrain had steep slopes towards the sea. First, the freshwater sediments were deposited in the low-lying areas and following the Holocene sea rise the sea reached the coastal landscape and only a few islands were not covered by sea water. The Holocene sediments contain a lot of organic material and they are not consolidated.

Along the shore, clayey till reaches large depths and are covered by thin Holocene marine deposits. Other glacial sediments occur very seldom.

The Danian and Selandian deposits are reached in a few boreholes.

The summary of the local model is:

A. Holocene marine and freshwater deposits, totally up to 10 m but often thinner

B. Clayey till with clay, silt and sand intercalations, up to 7 m thick

C. Meltwater deposits dominated by clay and silt, up to 18 m thick

D. Upper Clayey till, at least 10 m thick

E. Selandian and Danian deposits

A schematic section is seen in Fig. 17.

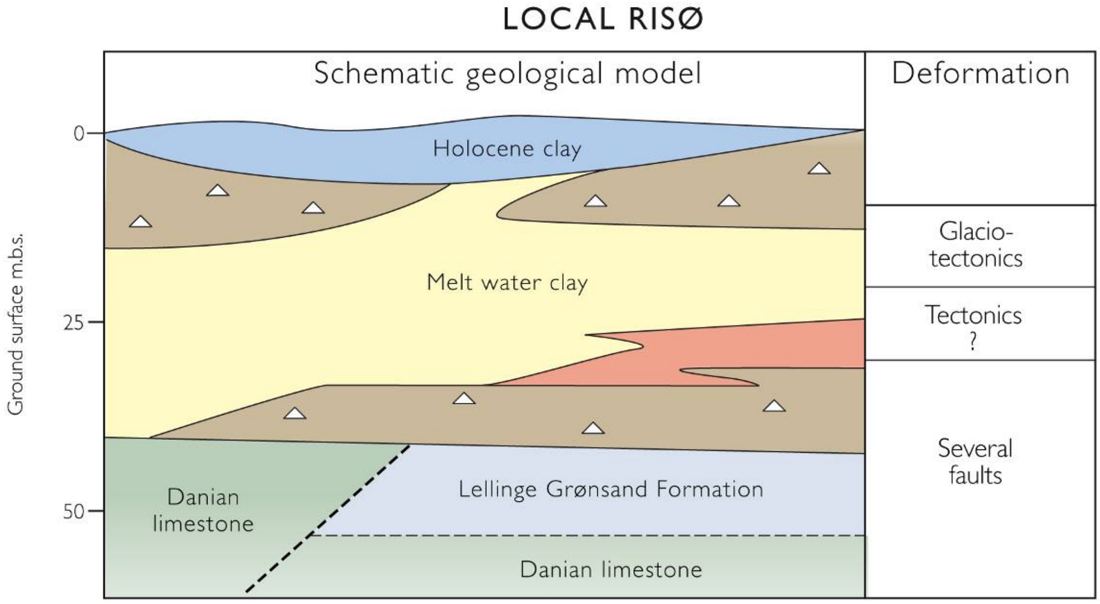


Figure 17. Schematic geological model for the local Risø area.

Model B. Regional model: The Quaternary and Paleogene deposits.

Model B is based on relatively few deeper boreholes from the Risø area but supplemented with a large amount of boreholes outside Risø. Four geological sections are constructed on borehole data (Figs. 18, 19, 20, 21) situated as shown on the figures. The sections documents important features of the structural framework of the area.

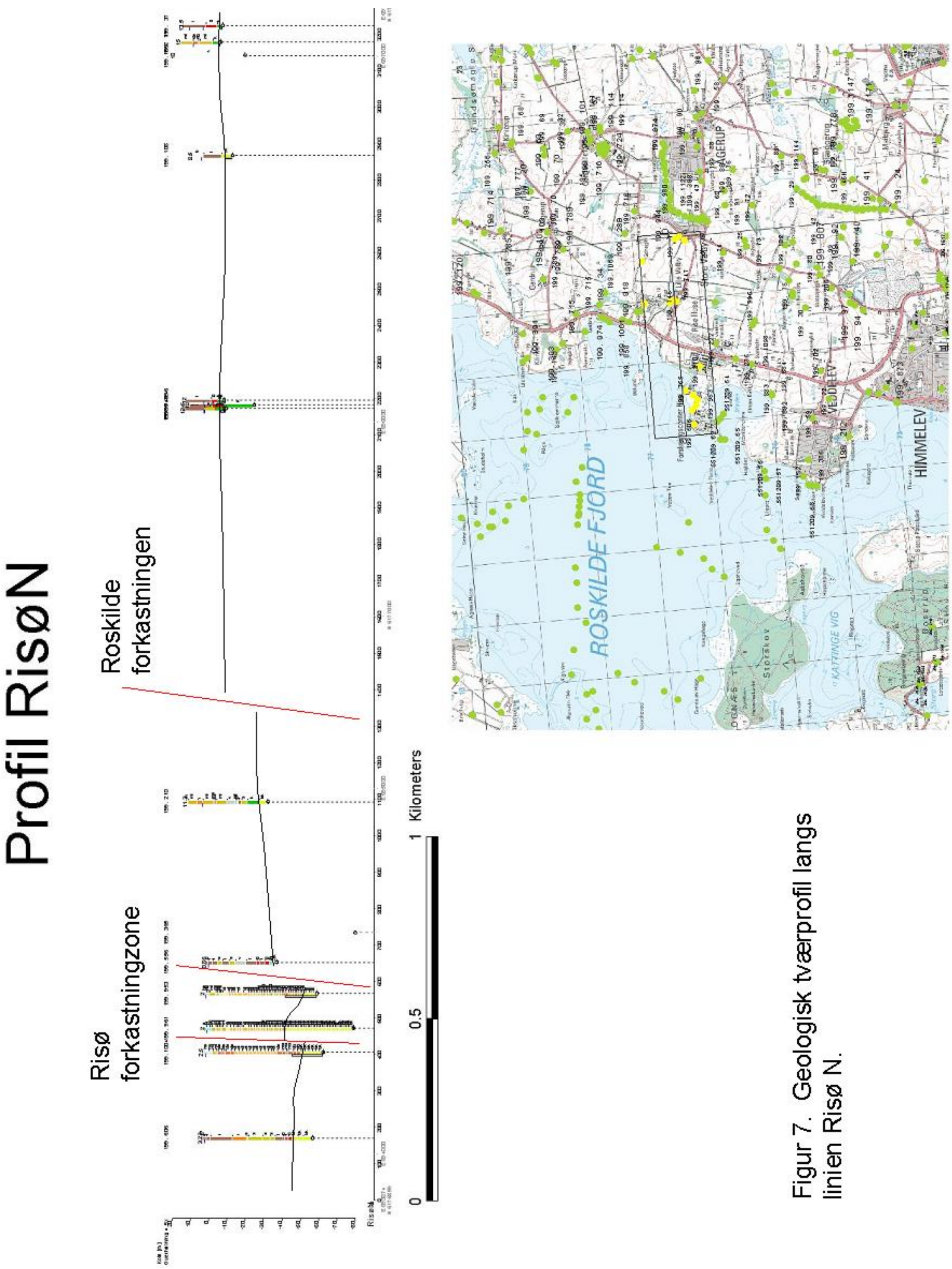


Figure 18. Geological section along the line Risø N (From Gravesen & Pedersen, 2005).

The main elements are two fault zones (normal faults) passing north-south through the area. Vertical movements can be seen in the layers from Danian and Selandian.

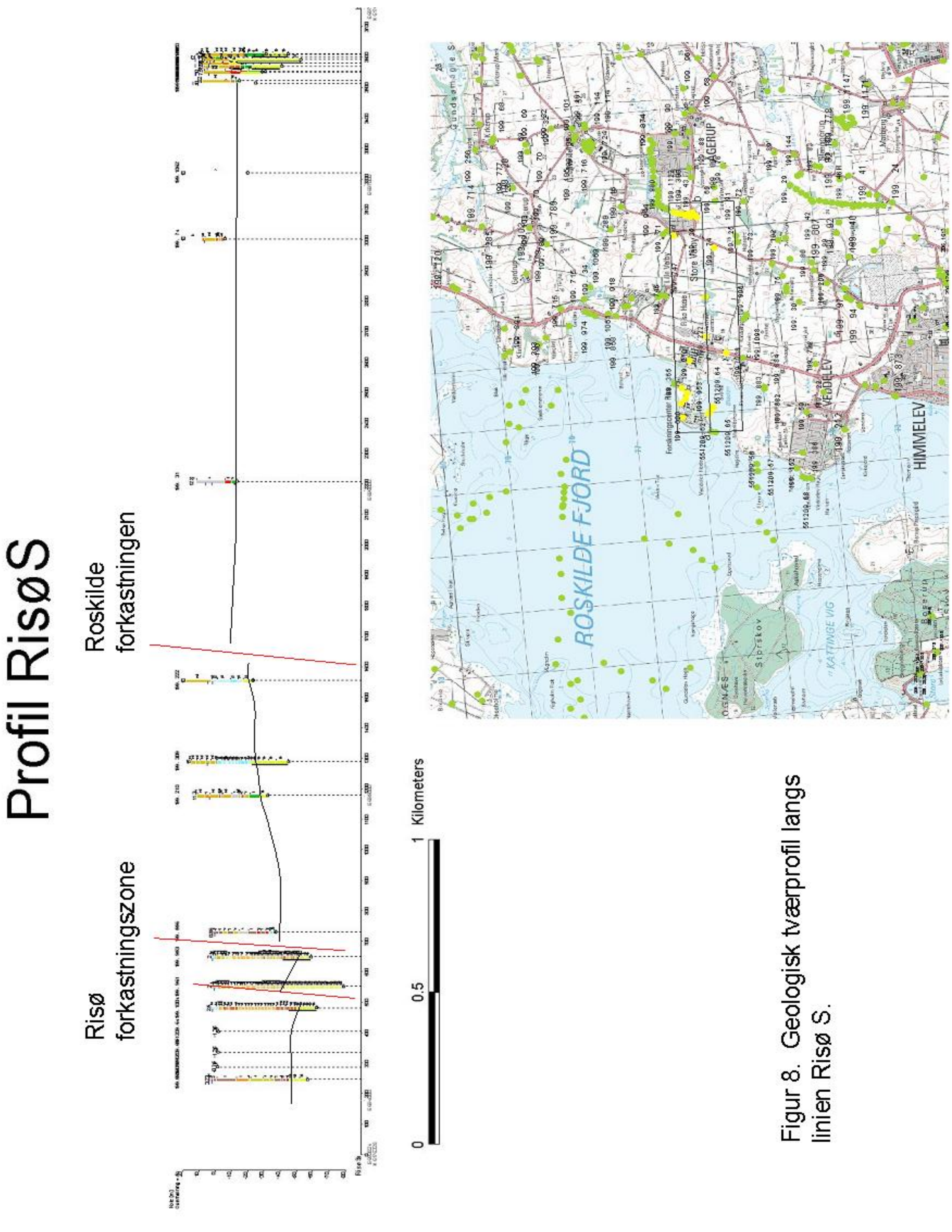


Figure 19. Geological section along the line Risø S (From Gravesen & Pedersen, 2005).

The Roskilde fault has been known as a main element in the structural build up of the deposits on Sjælland and can be followed towards the north and the south out of the Risø area. The Roskilde fault is situated towards the east close to the eastern boundary of the Risø area. The layers west of the fault have moved downwards and the Selandian deposits can be reached. The layers east of fault have moved upwards and only Danian deposits are found here. The difference between the layers on the two sides is approx. 10 m (spring high).

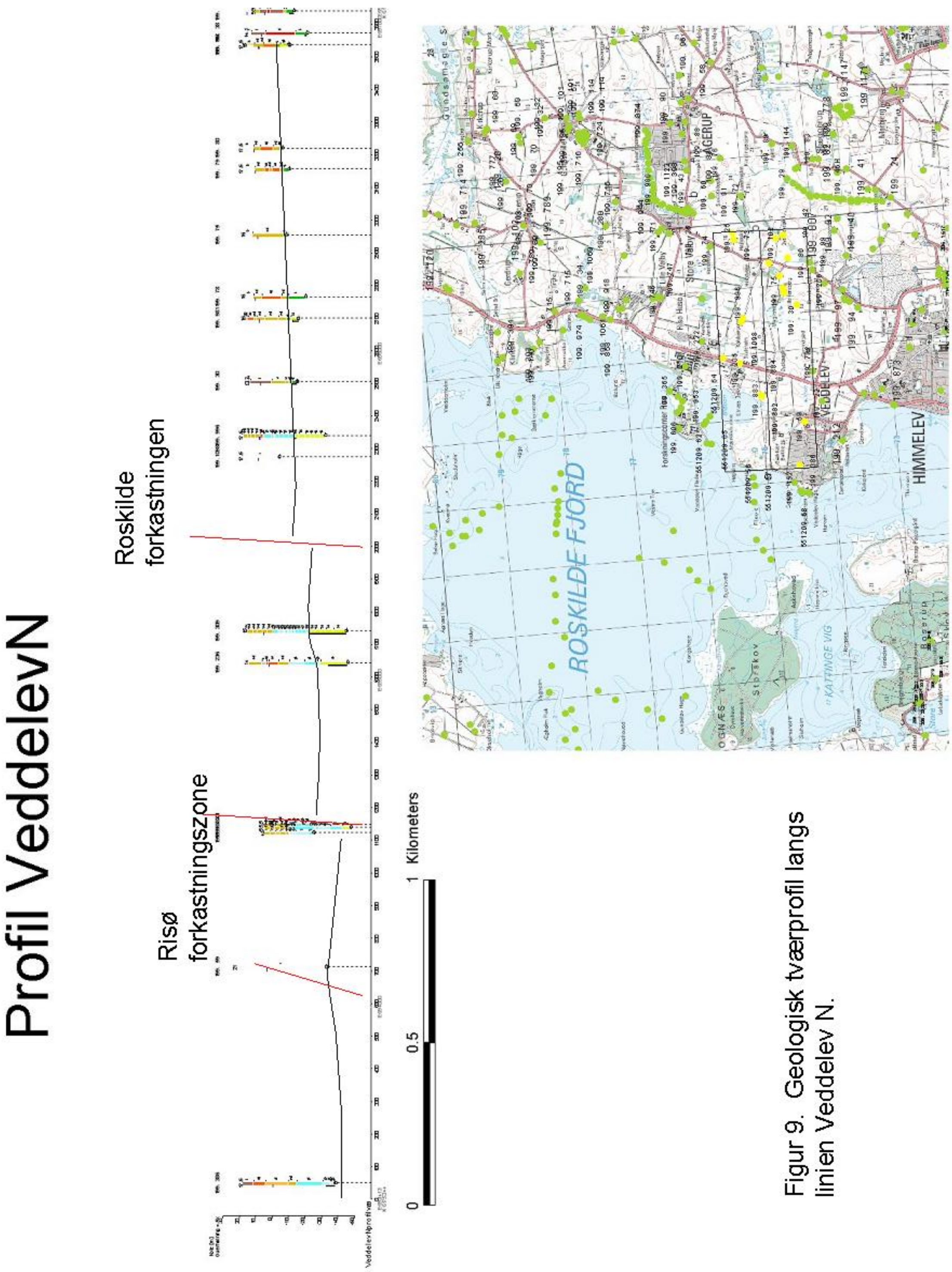


Figure 20. Geological section along the line Veddelev N. (From Gravesen & Pedersen, 2005).

Towards the west, two closely situated faults called the Risø Fault system show movements in the Danian layers. The faults are situated below the Risø peninsula and cut the southern part of the Risø area (Fig. 13 and 23). Both faults can be recognized on the four geological sections and to the north and the south (Figs. 18, 19, 20 and 21). Based on the existing information, the faults cannot be followed into the overlaying Quaternary deposits and therefore it cannot be determined whether recent tectonic movements (neotectonics) have occurred.

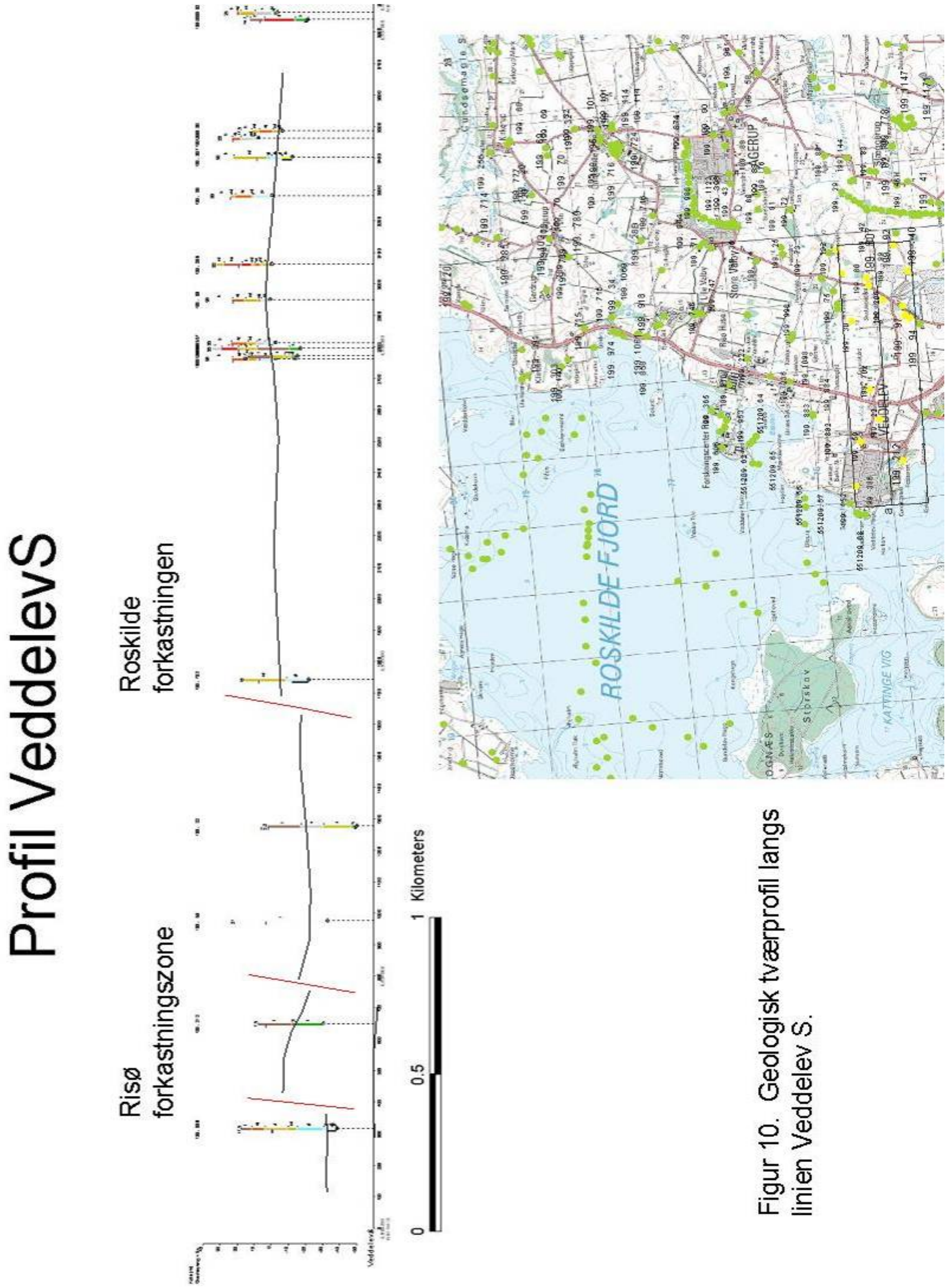


Figure 21. Geological section along the line Veddelev S (From Gravesen & Pedersen, 2005).

The Quaternary deposits have a thickness of 50 to 60 m laying over the Paleogene deposits and the faults (Fig. 22). It is possible to find the two clayey till units and few intercalated fine-grained meltwater deposits and below these an approx. 40 m thick series of fine-grained meltwater sediments over the Paleogene deposits.

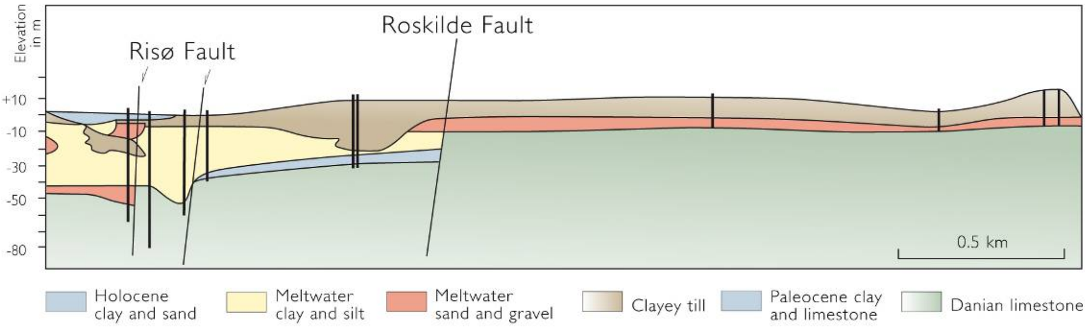


Figure 22. Interpreted geological section.

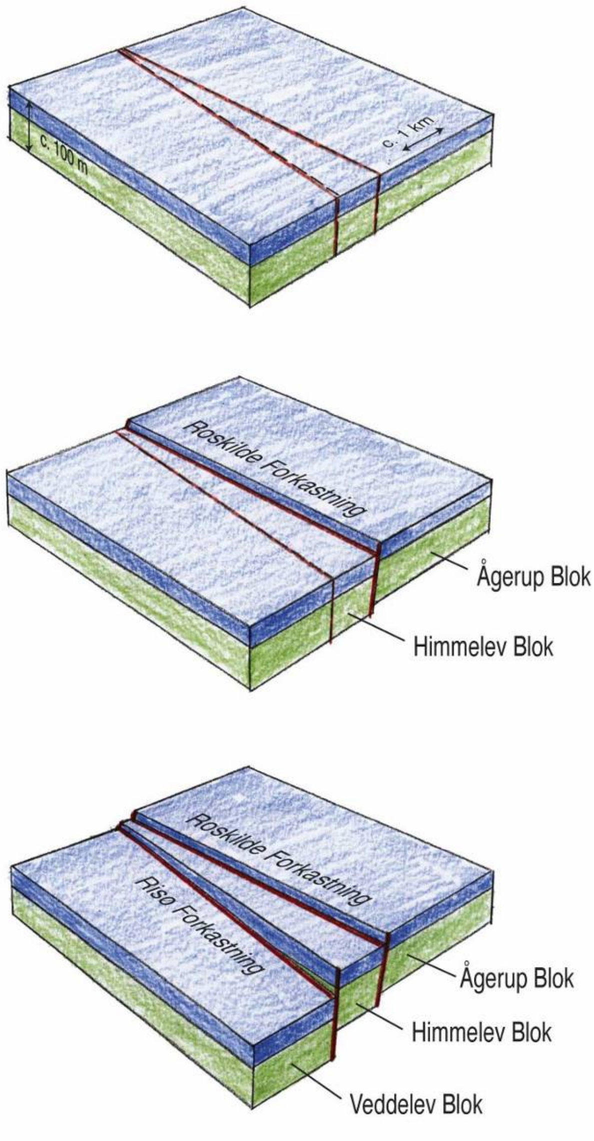


Figure 23. Model of the structural development of the pre-Quaternary conditions of Area 5 (Model B)(From Gravesen & Pedersen, 2005). Legend: Green: Danian deposits, Blue: Selandian deposits, Blok: Bloc, Forkastning: Fault. For explanation see the text.

Towards the east, the Quaternary deposits thin out and consist of clayey till above coarse-grained meltwater deposits. Towards Roskilde Fjord, the overlaying marine Holocene sediments are found. Few indications of glaciotectonic disturbances caused by push from a glacier in the Quaternary deposits are found in local model A.

Summary of the regional models is:

A. Holocene freshwater deposits (up to 4 m) and marine deposits (up to 7 m)

B. Upper clayey till, 5-10 m thick

C. Meltwater clay and silt, up to 20 m

D. Meltwater sand, up to 8 m

E. Lower clayey till, 10-15 m thick

F. Paleocene, Selandian limestone and clay. Thickness: few m and up to 30 m.

G. Paleocene, Danian limestone, thickness at least 35 m

A schematic geological model is seen in Fig. 24.

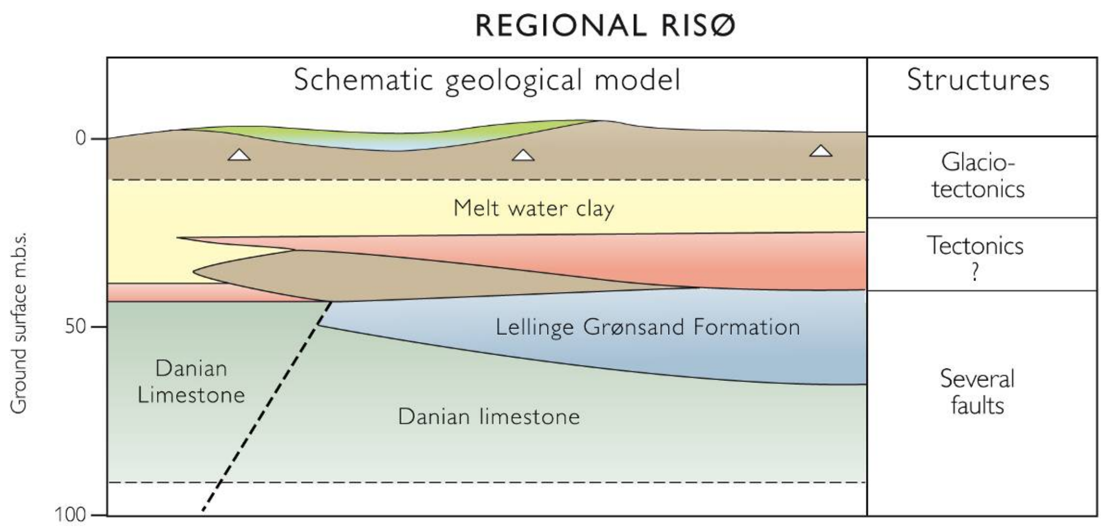


Figure 24. Schematic geological model of the regional Risø area.

5.6.4 Earthquake activity

Seismic activity in the area

The seismic station net in Denmark is run by GEUS and comprises 5 stations of which three stations are located on Sjælland: Gilleleje museum, Vestvolden, København and Lille Linde, Stevns (Fig. 25)(GEUS homepage: www.geus.dk).

Figure 25. The seismic stations in Denmark (From GEUS Homepage (www.geus.dk)).

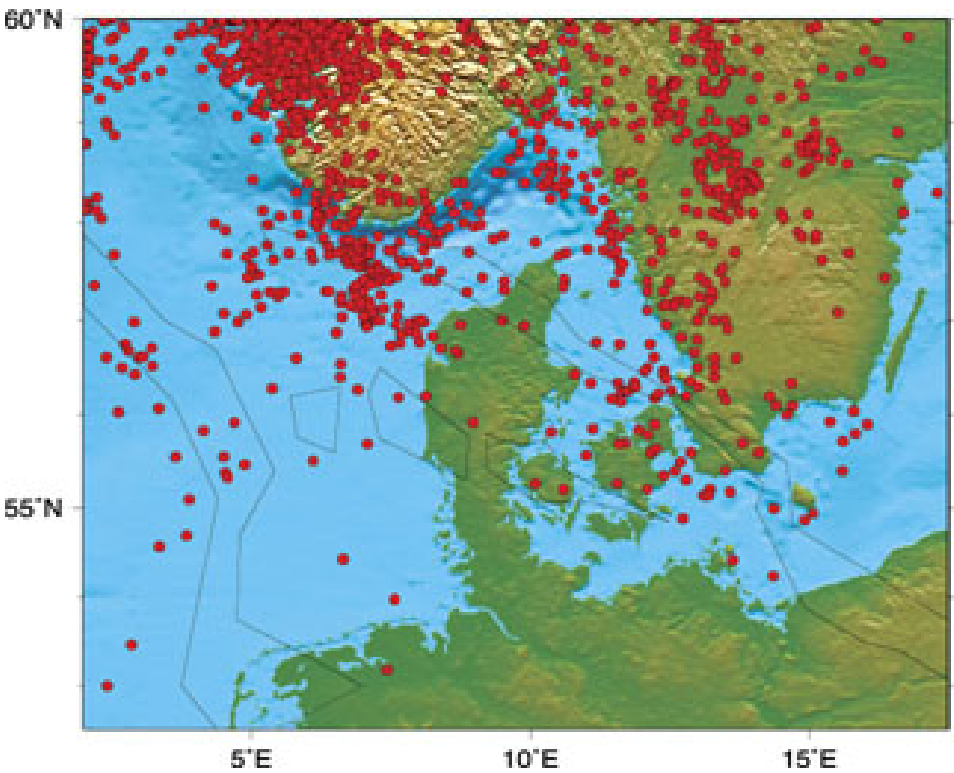


Figure 26. Map of the earthquake epicentres in Denmark and surrounding areas. A red dot shows the location. (From GEUS´s Home Page).

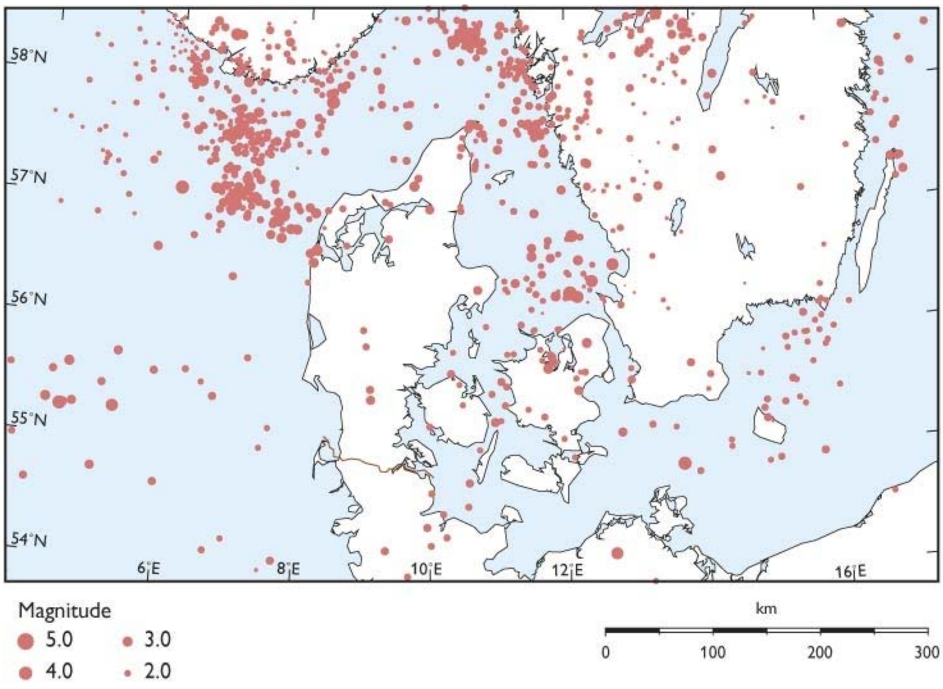


Figure 27. Earthquake epicentre in Denmark and surrounding areas from 1970 to 2008. Magnitude in Richter scale (After Larsen et al., 2008).

The earthquake activity is measured with respect to location, time and size. The activity in Denmark is very low compared to many other countries.

On Figs. 26 and 27, the registered earthquakes since 1929 are shown. The maps show that there have been seismic disturbances in the area of Risø and 3-4 earthquakes can possibly be related to the fault complex Roskilde-Risø and the continuations of the faults to the north and the south. The earthquakes in the Risø area are between 1.9 to approx. 4.5 on the Richter scale which is in the lower part of the scale but the movements can be recognised.

Earthquake risk conditions in relation to geological movements

The seismic activity on larger depth is difficult to relate directly to the more near surface layers. The rise of the land area is probably a slow process, while earthquakes are faster movements. The shown faults in the Paleogene deposits can partly be traced to larger depth but not upwards to the ground surface.

Therefore, it is impossible to relate recent seismic activity to the many faults and fractures in the sediments. Other signs of recent movements along the faults and fractures have not been proven.

5.7 Ground stability

The ground stability in the area seems to be good. The fault systems have to be considered in relation to the earthquake activity.

5.8 Groundwater hydrogeology

5.8.1 Groundwater characteristics

The research centre Risø, Sjælland (Area 5) is situated in an area with one shallow and two regional groundwater bodies as shown in Figs. 28 and 29. However, only the limestone aquifer is present right underneath the Risø location. Deep groundwater bodies have not been identified in or near Area 5 in the catchment management plan from the Ministry of Environment. The subdivision into groundwater bodies is described as part of the basis analysis carried out by the former Region Hovedstaden in the technical report by Vanddistrikt HUR in 2006. The overall assessment of the chemical and quantitative status of the shallow groundwater body (DK2.2.1.1) is poor, due to a poor qualitative status (see Section 5.9).

The overall assessment of the regional limestone groundwater body DK2.2.2.12 is categorized as poor, because the quantitative conditions in DK2.2.2.12 do not meet the requirements.

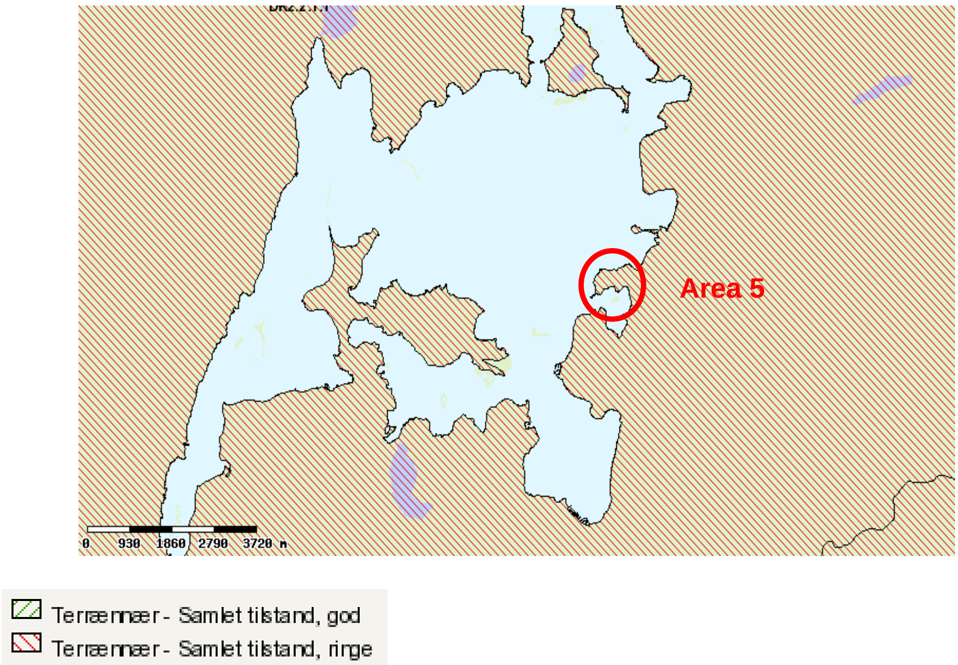


Figure 28. Shallow (or terrain near) groundwater body DK2.2.1.1 nearby Risø (Area 5). The overall assessment of chemical and quantitative status: poor status (Red shaded area). It has been assessed by the Environmental Centre that there are local drinking water inter-

ests in the shallow groundwater body (DK2.2.1.1)(From the Ministry of Environment, 2010a).

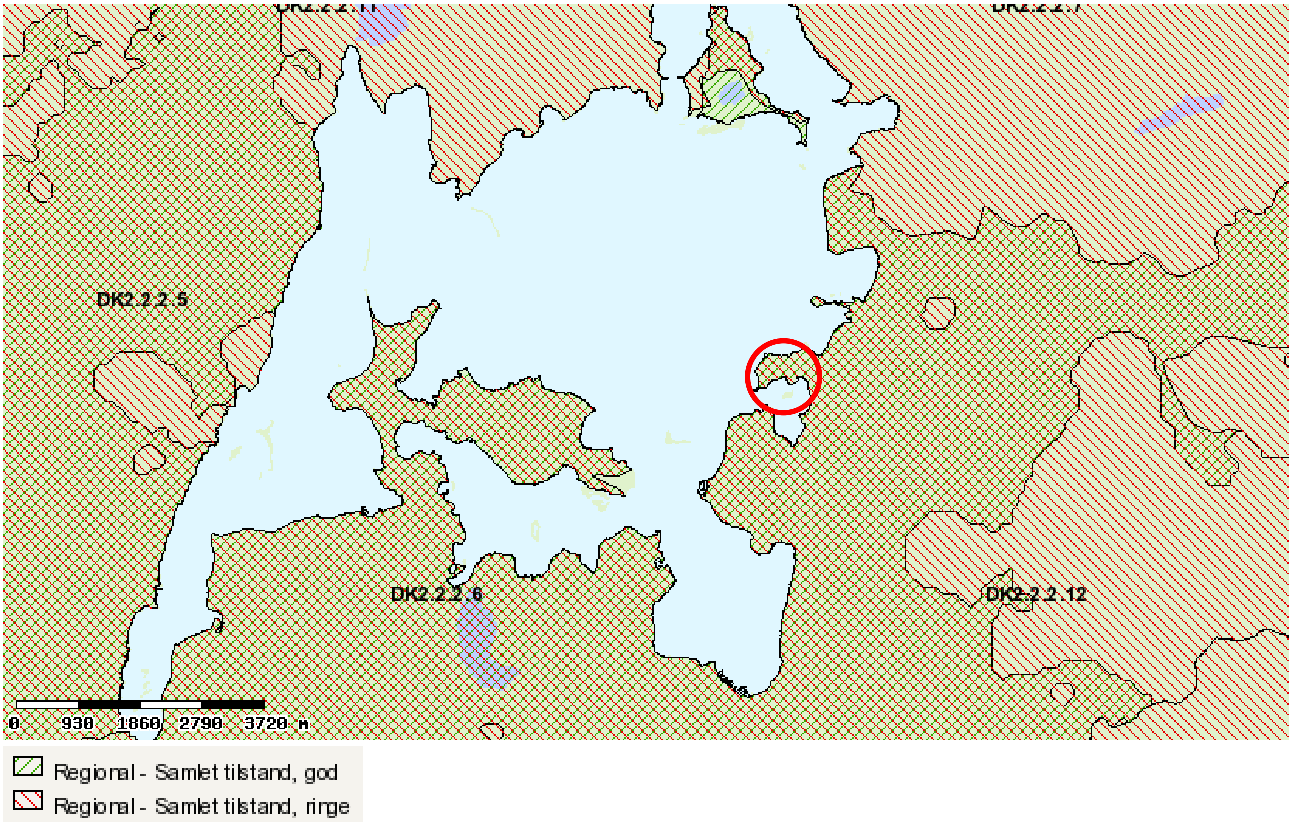


Figure 29. Regional groundwater bodies in the Roskilde Fjord region. Nearby the Research centre Risø (Area 5) two regional groundwater bodies are indicated at the map: DK2.2.2.6 (meltwater sand aquifer) above DK2.2.2.12 (limestone aquifer). However, only the limestone aquifer is present right underneath the Risø location. The overall assessment of chemical and quantitative status: poor status (Red shaded area) in DK2.2.2.6 and good status (green shaded area) in DK2.2.2.12 (From the Ministry of Environment, 2010a).

The groundwater level was measured when the boreholes were drilled in the limestone (at different time) during the period 1956-1991.

On the peninsula and the near shore, where the terrain is situated just above the sea level (elevation + 2 m to + 2.5 m), the groundwater level in the underlying limestone aquifer was also near the sea level (elevation + 0.65 m to + 1.9 m).

On the land area, the ground surface is lying much higher (+11.3 m to 24 m) and the depth to the groundwater level in the underlying limestone aquifer is larger (+ 2.8 m to + 4.8 m).

The potentiometric head in the glacial till aquitard is unknown within area 5.

Development in groundwater potential

Risø abstracts groundwater from the Danian and Selandian deposits at own Water Work in the area east of Frederiksborgvej. Information about the groundwater levels is available from the wells mainly from 1979 to 2001. The groundwater levels in the limestone aquifer were situated between levels + 3 m and + 6 m with fluctuations. The potentiometric head in the overlying glacial till is uncertain.

The limestone aquifer is artesian with the pressure head in the clayey till cover. A potentiometric map of the Danian-Selandian reservoirs is seen in Fig. 30., which shows levels between + 2 m and + 4 m in the eastern part of area 5. In the landside area is the unsaturated zone in the glacial till assessed to be between 2 and 5 meter deep. A fluctuation of the groundwater level will follow the precipitation during the year.

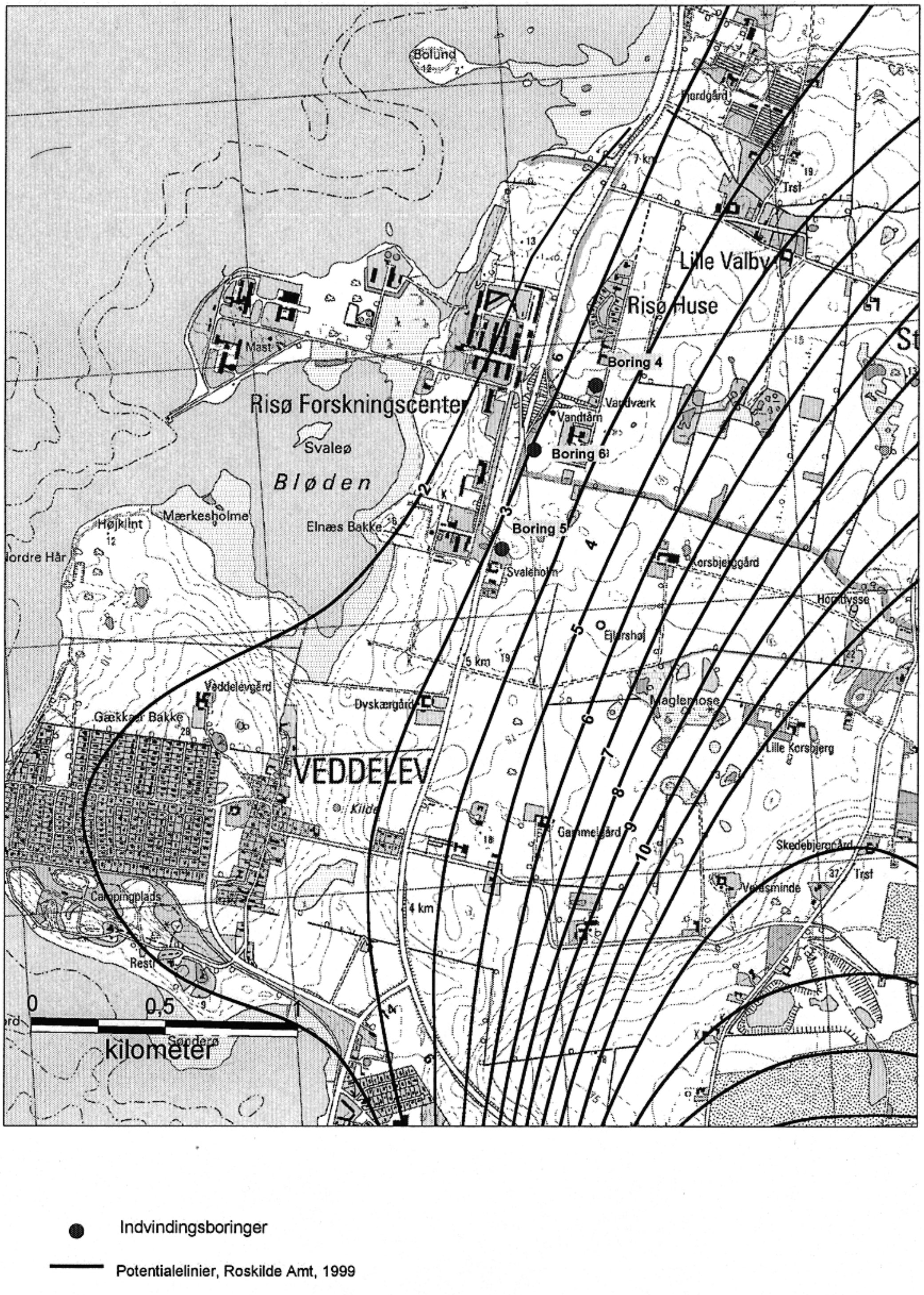


Figure 30. Map of the groundwater potential lines in the limestone aquifer (From Niras, 2004). Legend: Dot: Water supply wells, lines: Equipotential lines.

Groundwater flow

The groundwater flow is primary from east towards west into Roskilde Fjord as the direction is perpendicular on the potential lines. On the peninsula it is expected that the groundwater flow is towards the fjord.

Leaching and transport

The groundwater reservoirs in the area are covered by clayey tills to the east. The conditions on the peninsula with Holocene deposits and few sand layers are less clear.

In general, the clayey tills has double porosity media properties with water transport in both the small micropores between the particles in matrix and in the larger fractures, sand lenses and biopores. Several clayey till studies in Denmark have shown that fractures can reach to 8 to 10 m depth and more seldom to 15 m depth. However, the depth of the fractures within Area 5 has not been investigated.

Below the clayey till, the water percolation will happen through the fine-grained meltwater deposits with a slow transport in clay and silt and faster in the thin sand layers.

5.8.2 Drinking water areas

The groundwater has to be protected to ensure that our current and future need for clean drinking water can be met. It is the Environmental Centres (former counties) responsibility to do the planning, based on the two criteria: First, to make sure that the future necessary quantity of clean groundwater can be abstracted. Secondly, the groundwater aquifers must be protected against recent and future pollution.

As part of the Danish Government´s efforts to protect groundwater, the Environmental Centres have designated areas of major groundwater aquifers, so-called OSD-areas. OSD stands for "Areas of special drinking water interests” (Fig. 31).

The rest of the country is divided into "Areas with water interests" (OD-areas) where good sources of drinking water are also located and "Areas with limited drinking water interests", where it is difficult or impossible to obtain good groundwater quality because the water is more or less contaminated.

The drinking water areas categorised by the Environmental Centre Roskilde (Miljøministeriet, 2010a) for the Risø area is shown in Fig. 32. The Risø peninsula and the area East of Risø is categorized as an area with limited drinking water interest. However, it should be noted that only few km east and south of Risø, the groundwater aquifers has special drinking water interests. Fortunately, the groundwater flow in the regional limestone and meltwater sand aquifers, respectively, have a western direction (see Fig. 30).

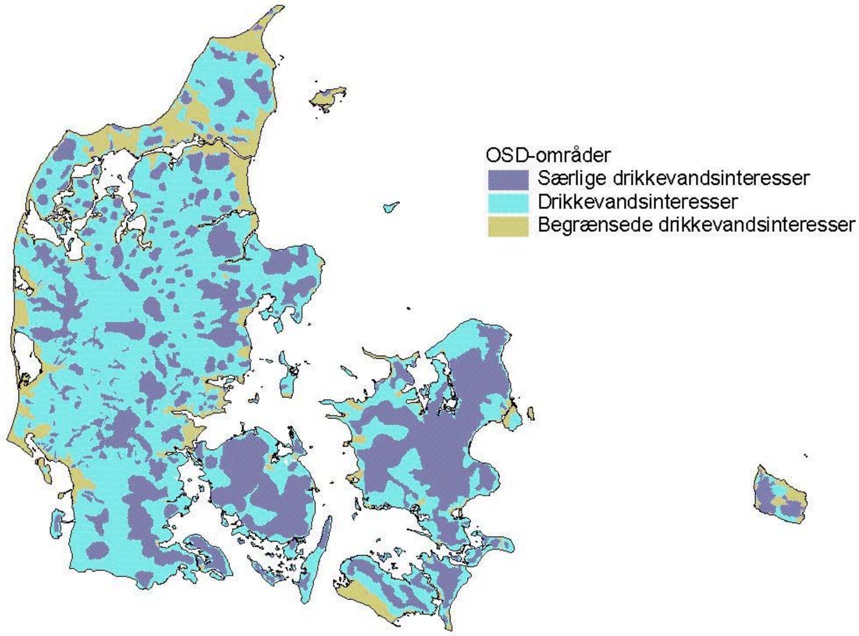


Figure 31. Map of three categories if drinking water interest in Denmark. The areas of special recharge groundwater and drinking water interests (OSD areas protected by law) are in dark blue colour. The areas shown with light blue colour are areas of some interest for drinking water purposes. The areas in brown colour are areas of limited (or none) drinking water interests.

The Risø area is situated in an OD area with some drinking water interests (see below). The Research Centre has its own Water Work which supplies drinking water and research water from three wells situated east of Frederiksborgvej (Fig. 6).

Figure 32. Various drinking water areas situated at the Risø peninsula and surrounding. Dark Blue: Areas of special drinking water interests; Light blue: Areas of some drinking water interests; Yellow: Areas with limited or none drinking water interests (http://kort.arealinfo.dk/).

5.9 Groundwater chemistry

The overall groundwater quality aiming for drinking water purpose has been assessed by the former Region Hovedstaden and Environmental Centre Roskilde for each groundwater body and reported in the catchment management plan “Hovedopland 2.2, Isefjord and Roskilde Fjords”. The shallow groundwater body DK2.2.1.1 has a poor status due to findings of nitrate and pesticides in concentrations that exceed the acceptable limits in groundwater. The regional groundwater body 2.2.12 has a good chemical status as it meets all essential requirements for a good groundwater quality. However, the total assessment of DK2.2.2.12 is poor due to the poor quantitative status of the regional limestone groundwater body.

The coastline and fjord coastal water outside Area 5 is given NATURA2000 habitat status. However, there are no further restrictions in accordance to Naturbeskyttelsesloven (law for nature protection) directly within Area 5. In spite of the vicinity of Area 5 to the shoreline of Roskilde Fjord, the position of the salt/freshwater transition is not expected to be influenced because of the relatively low salinity in the fjord water. Groundwater abstraction wells placed at the eastern side of the road Frederiksborgvej show chloride contents of 25-50mg Cl/L.

5.10 Climate and climate changes

5.10.1 The present climate and scenarios for the future

Models and forecasts for the future changes of the global climate the next 100 years point towards increasing temperature and precipitation. At present, the annual mean temperature is c. 8 ^{o}C in Denmark. The national average (corrected) yearly mean precipitation for the most recent standard period (1961 – 90) was 826 mm. Since then, the precipitation has increased by c. 4.5 %. The models performed by DMI show an increase in temperature of 3-5^{o} C and lesser precipitation during the summer (75-90 %) and more precipitation during the winter (110-140 %). Besides this, more extreme incidences will occur with more storms, higher sea level and increased flooding.

5.10.2 Changes in the sea level

The global sea level rise happens because of melting of the world's glaciers and expansion of the sea water caused by temperature increase. The models (IPCC) give different figures for the rise the next 100 years. At present, the best suggestion of the sea level rise is between 0.4 and 0.75 m. Plus an additional approx. 30 cm caused by changes in the wind pattern. The actual climate and the expected future changes are described in more details in Gravesen et al. (2010, Report no. 2).

Parts of the Risø area on the peninsula and the beach meadow are situated close to the present sea level, between 0 and +1.0 m. Most of the land area is higher. The consequences for Roskilde Fjord of a sea level rise of 50 cm in the Danish area are difficult to forecast. Some parts of the Risø peninsula will be flooded but the vertical land rise may contradict the sea level rise.

During the last 100 years, a small sea level rise has happen and values of the relative sea level rise at stations close Roskilde Fjord are between + 0.1 mm and 0.3 mm per year.
The Roskilde area is not especially exposed for "local" storms and flooding because of the geographical situation in the inner part of the fjord although it is a western exposed coast where most activity occurs. Otherwise, relatively large meteorologically induced sea level variations, controlled by the water exchange between the North Sea and the Baltic do propagate to the interior parts of Roskilde Fjord. (The range of the semidiurnal tide is less than 25 cm in the area). A sea level rise and more frequent storms will influence the area but the size of the consequences is uncertain.

5.10.3 Changes of the coastline

An evaluation of the coastline changes between 1896 and 2001 is shown on Fig. 33. Only minor erosion has occurred along the clayey till cliff towards the west and some re-sedimentation of the material in the small bays and along the coastline.

This is in accordance with erosion rates of 0-0.1 m per year at lesser exposed inner coasts in Denmark. Future sea level rise and storms can change these conditions.

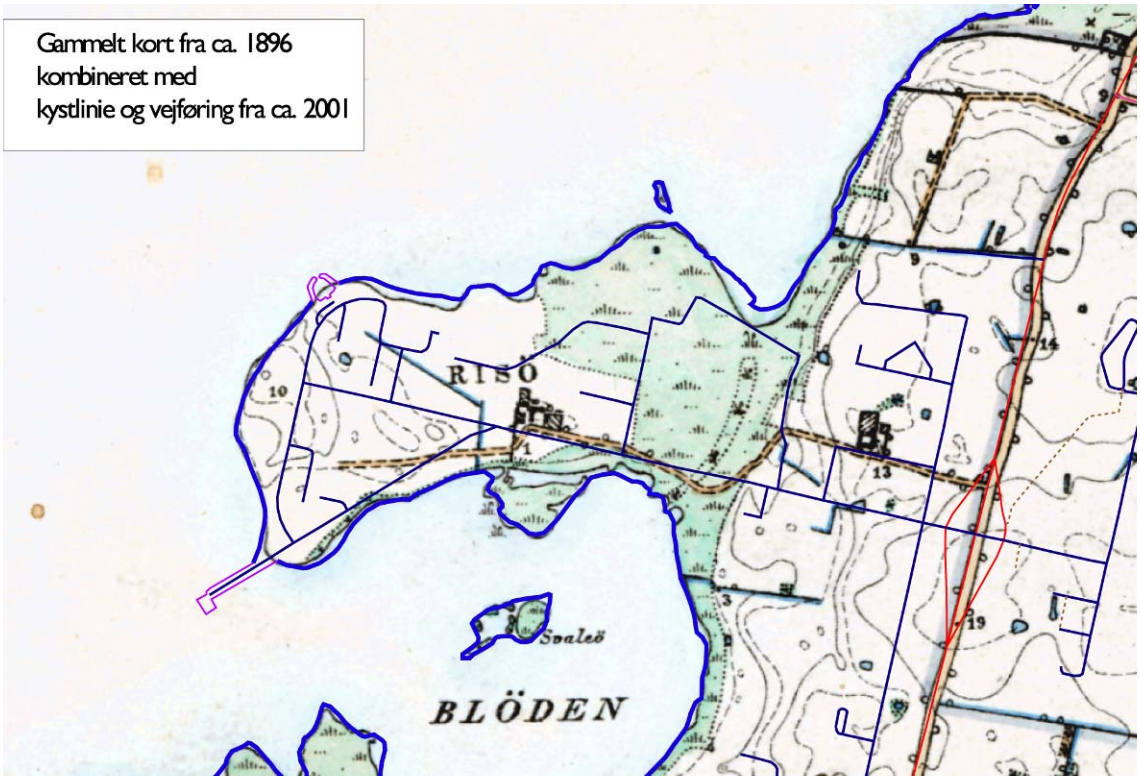


Figure 33. Map of the area showing the change of the coastline caused by erosion and sedimentation. Combination of maps from 1896 and 2001 (KMS).

5.10.4 Changes in groundwater conditions

Increased precipitation rates seen in a future climate perspective will probably not cause a much larger groundwater recharge. Climate model studies indicate a relatively higher run off to surface water bodies as surface and via terrain near groundwater aquifers. Higher air temperature will also give higher temperature in the groundwater and changed characteristics in relation e.g. to corrosion.

5.11 Restrictions and limitations

Protected areas have only restricted distribution in Area 5. NATURA 2000 areas are found just outside the area (Fig. 34).

There is no raw materials interest in the area. Saltwater intrusion is not expected to be of importance even at higher sea levels in the Roskilde Fjord as results of climate change.

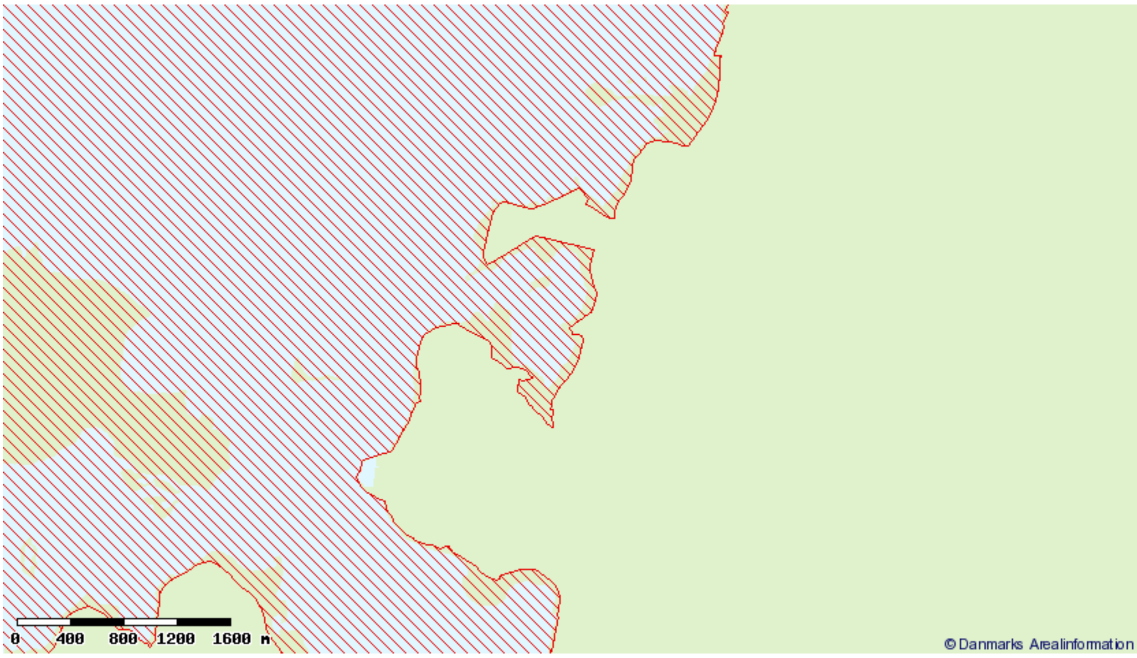


Figure 34. NATURA2000 areas on the sea are bordering up to the coast of Roskilde Fjord including the Risø area.

5.12 Summary of the area conditions

Amount of data:
General sparse but many shallow wells within the Research Centre Risø area. No geophysical and chemical data.

Homogeneous conditions and isolation of the waste by low, permeability layers:
Relatively homogeneous conditions in the Quaternary deposits down to approx. 25 m. Very few information about the deep layers and the fracture system in this layers. The glacial deposits and pre–Quaternary layers have both double porosity in matrix and fractures. The sediment types in the area will probably have a weak to moderate protection against long-term dilution.

Stability
Good stability on surface and depth.

Seismic activity and tectonic movements
Two fault zones are crossing the area: Roskilde and Risø, both also known outside the area and the fault zones have regional importance. The faults are found in the pre-Quaternary deposits but have not been demonstrated in the Quaternary layers. Seismic activity is measured in close connection to the fault zones but it is not possible to describe the present importance and problems.

Groundwater flow conditions
The artesian groundwater reservoir conditions in the deposits are related to the Paleogene reservoir. The groundwater flow conditions in the Quaternary cover are less well-known. The groundwater flow is directed towards west into Roskilde Fjord.

Dilution of pollution and retention of pollution
No Danish studies have been carried to document dilution capabilities or retention of radio-nucleides in glacial till sediments.

Drinking water interests
The area is an OD area and a major OSD area is located towards the east. An up-gradient location of the well field for the Copenhagen Energy water supply need special attention. In addition, minor local water supplies exist in the area including water supplies to the Research Centre Risø .

Groundwater chemistry, non- aggressive components
The groundwater contains apparently no aggressive components. Future sea level rise can increase thesodium chloride content in the groundwater.

Ground surface conditions
Processes on the ground surface should not give problems on a potential disposal.

Climate extreme conditions and sea level rise
Climate changes, extremes as storms and heavy precipitation and future sea level rise will have some influence on the area.

Other restrictions
No other restrictions will give problems.

5.13 Final Remarks

At present, the Risø area, the Research Centre Risø, store the waste and the reactor buildings that are going to be demolished. The conditions of the area in relation to be a potential waste disposal has been described above and these conditions have to be evaluated in relation to the other possible areas.

6. Area 6. Stevns, East of Store Heddinge, South Sjælland

6.1 The location of the area

The area is located on the easternmost part of the peninsula Stevns in south Sjælland (Fig 35). The area is delineated by a north - south line just east of Store Heddinge and the eastern boundary is Baltic Sea (Fig 36).

Figure 35. Location of the area. Stevns is located on the eastern part of south Sjælland. East Denmark.

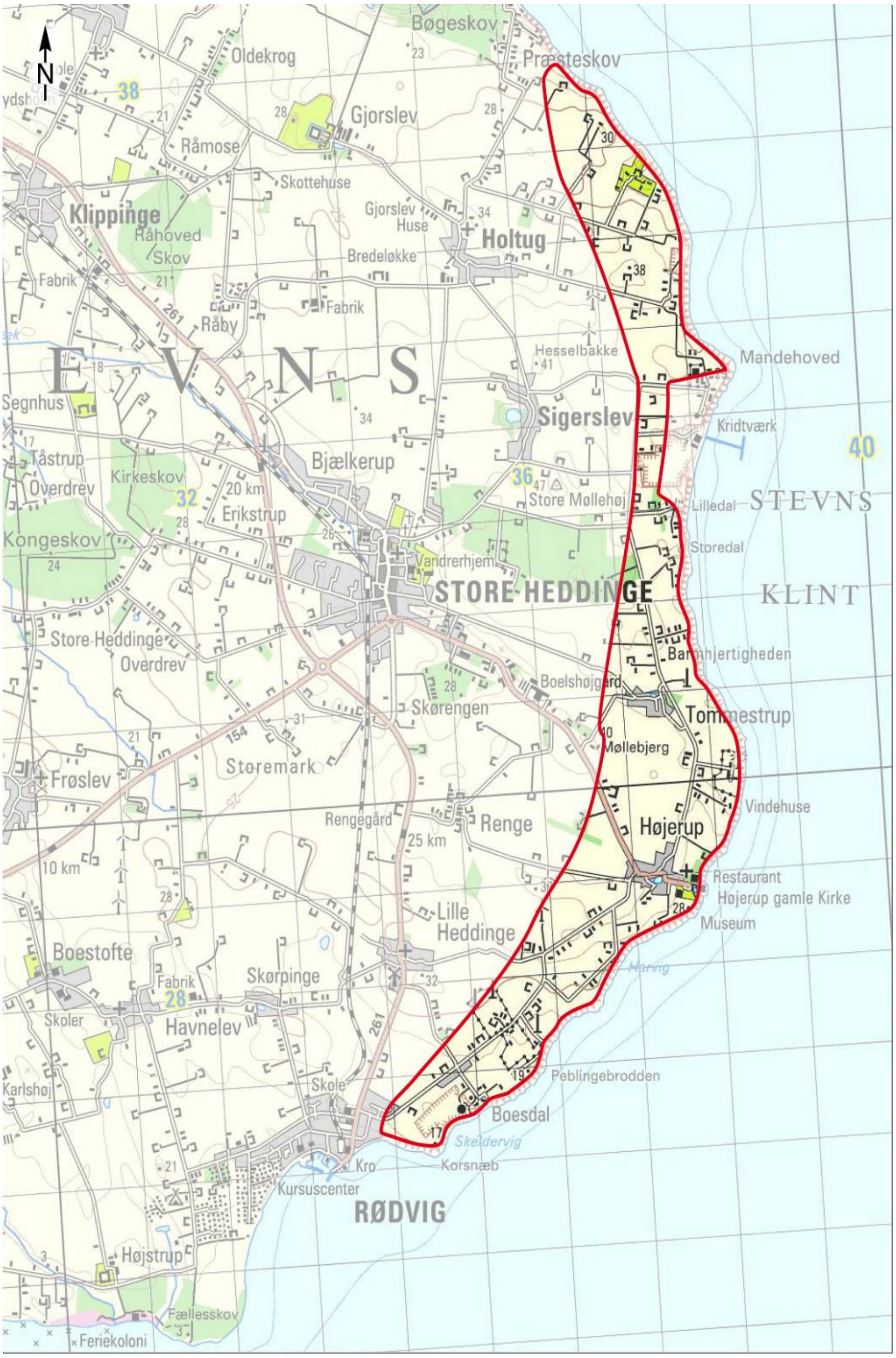


Figure 36. A detailed map of Area 5. Area 5 is located on the eastern part of the Stevns peninsula.

6.2 Terrain, topography and processes

The area is located on the eastern part of the Stevns peninsula, along and landwards the coastal cliff. The length of the area is c. 13.3 km, the width range from 0.3 to 1.6 km and the area is c. 12 km^2.

The landscape between the villages Tommestrup and Højerup and further toward the north to west of the headland Mandehoved is a very flat terrain, almost without undulations and situated at levels between c. 25 and 35 meters above sea level (m.a.s.). The landscapes of the southern and northern parts of the Area 6 are slightly more undulating. In the northern section, the level reaches 38 m.a.s. In the southern section, the level is decreasing to c. 15 m.a.s.

Except from village ponds in Højerup and Tommestrup, and (rain) water filled hollows in Sigersted chalk pit, no lakes or streams are found in Area 6.

The area includes the villages Højerup and Tommestrup, Sigersted chalk pit; the Fortress of Stevns (northeast of Boesdal) one mainor road (between Store Heddinge and Højerup) and a number of smaller roads. The remaining and predominant part of the area is used for agriculture with scattered houses primarily located along the roads.

Owing to the low relief and the relatively intensive cultivation, the surface processes (soil creep, frost – thaw processes, soil development etc.) proceed slowly and undramatic. The by far most dynamic processes are found in the coastal zone bordering the eastern delimitation of the area. The chalk cliff is erosive and the major part of the cliff is unprotected why slides and falls do occur.

6.3 Surface geology and profiles

The geology of the surface deposits is totally dominated by clayey till (Fig. 37). The area is interpreted as a basal moraine plain above limestone/chalk deposits. The Quaternary tills and the pre-Quaternary limestones and chalks are exposed in the cliff Stevns Klint and in the limestone/chalk pits.

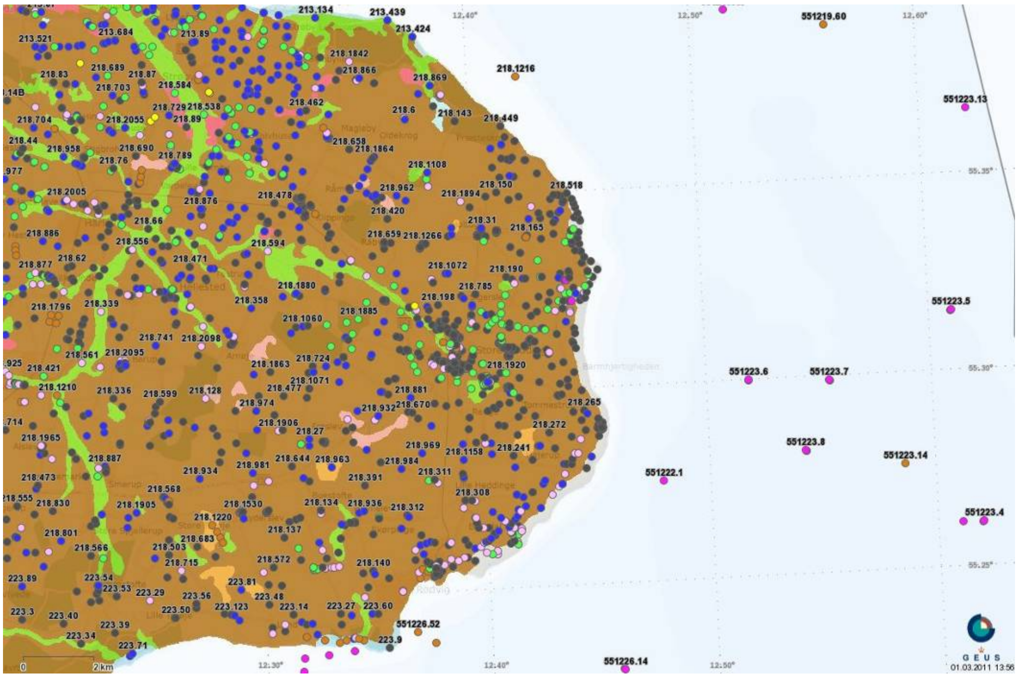


Figure 37. Map of the Quaternary deposits (From GEUS Homepage, After Pedersen, 1989). Legend: Brown: Clayey till, Orange: Meltwater sand, Green: Holocene freshwater deposits. Borehole legend: See Fig. 38.

6.4 Boreholes

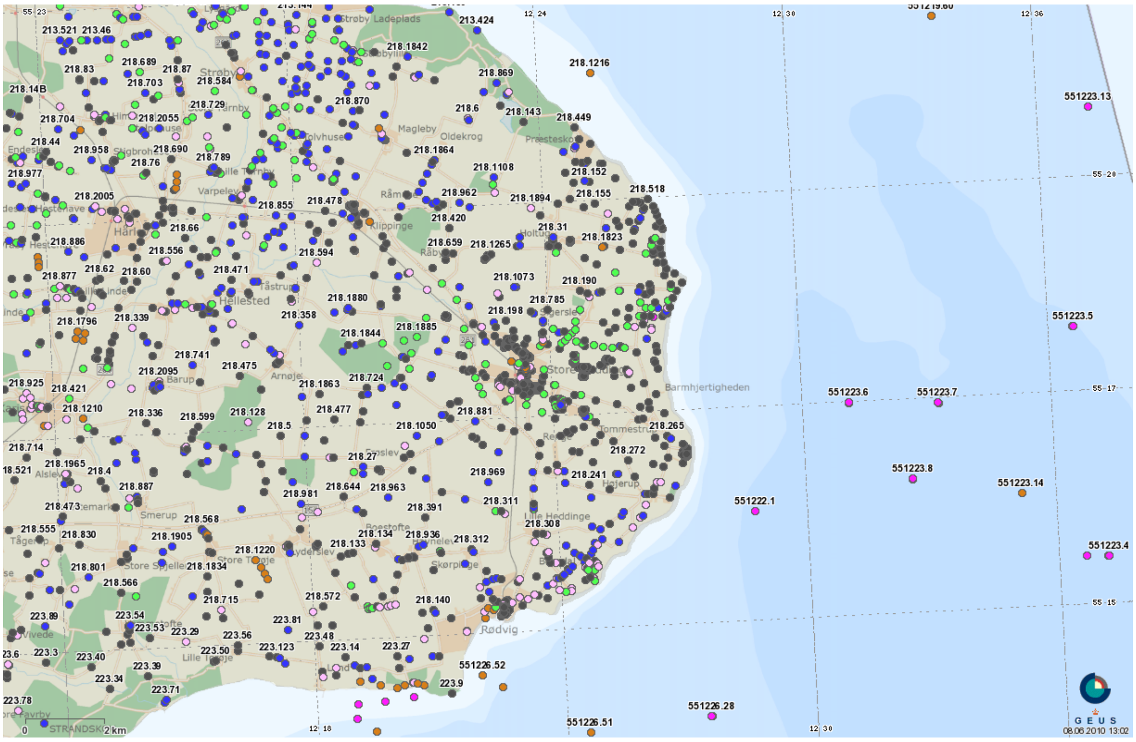


Figure 38. Map of the locations of boreholes from the Jupiter database at GEUS. Legend: 218.957: DGU no., Blue dot: Water supply well, Red dot: Geotechnical borehole, Pink dot: Raw material borehole, Green dot: Other borehole, Light red dots: Abandoned borehole, Black dot: Unknown purpose.

The area is penetrated by many boreholes of which the main part are water supply wells but also raw material wells in relation to several chalk pit exists (Figs. 38 and 39). Most of the samples from the boreholes are ditch samples and it is often difficult in lithological description of the samples to differentiate between the limestone and chalk units. Several samples have been dated by use of foraminifera.

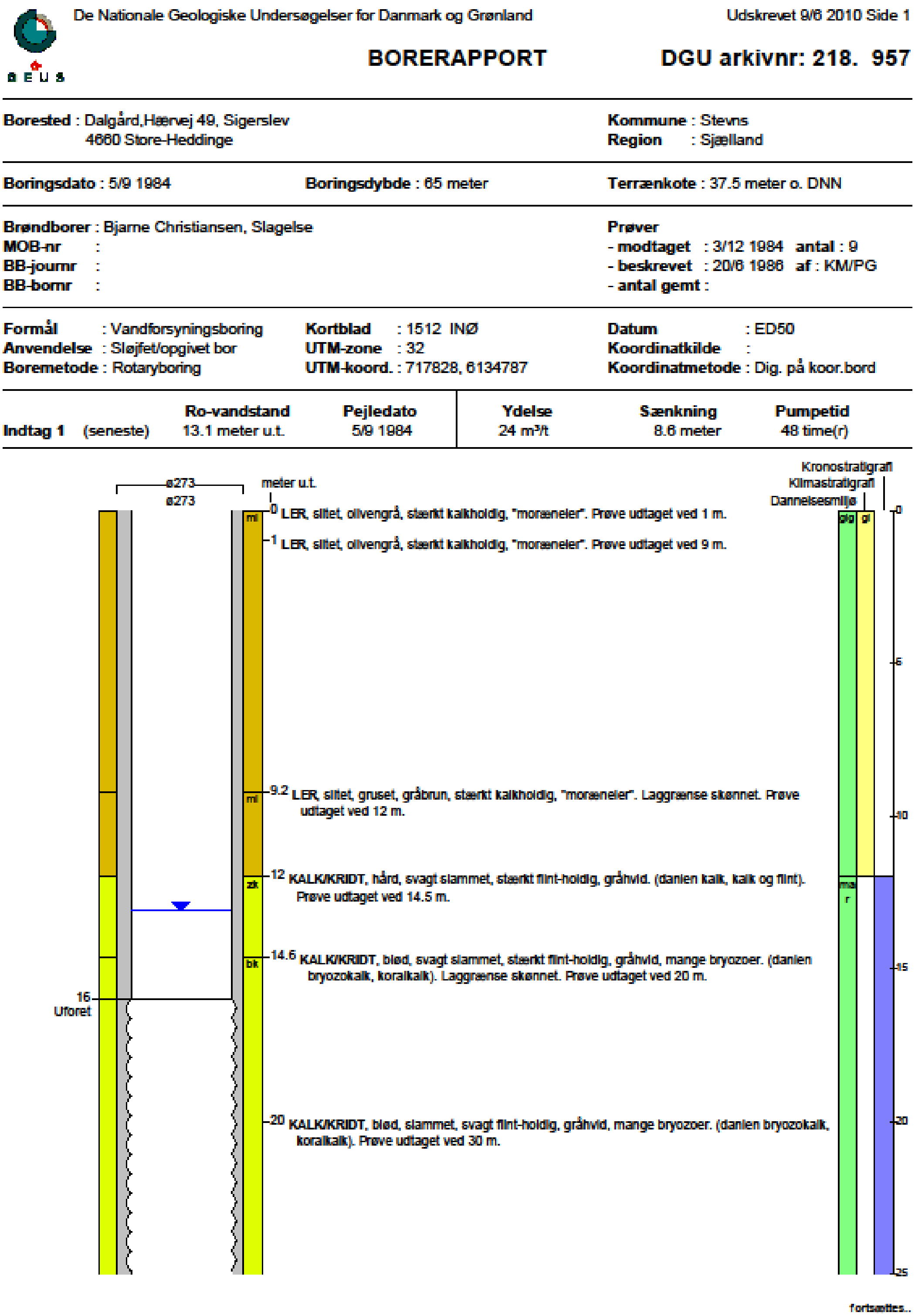


Figure 39. Geological log of borehole DGU No. 218.957. Upper part of the 65 m deep borehole. Legend: Brown (ML): Clayey till, Green: (BK): Danian limestone.

6.5 Sediment and rock characteristics, mineralogy and chemistry

6.5.1 Pre-Quaternary deposits

The pre-Quaternary sediments consist of calcium carbonate rich deposits from the Maastrichtian (Cretaceous) and the Danian (Paleocene). The relationship between the sediments is demonstrated in the cliff along the Stevns coast from Rødvig towards the south to Præsteskov towards the north (Figs. 40 and 42). From the chalk and limestone pits at Rødvig, Sigerslev and Holtug further information is available. The Cretaceous-Tertiary Boundary (Maastrichtian- Danian Boundary) is marked by the change from bryozoans chalk to the Fiskeler Unit.

Figure 40. The cliff Stevns Klint seen from Højerup towards north.

Maastrictian

The Upper Maastrichtian chalk (Tor Formation, Sigerslev Member) is homogeneous, soft, and white and has a content of black chert (flint) nodules in discontinuous undulating layers. Part of the unit consists of mound-bedded bryozoans-rich chalk passing up into gently wavy horizontally bedded chalk which is more than 70 m thick. The uppermost part of the chalk (Tor Formation, Højerup Member) has a more white grey colour (called "gråkridt") and content of bryozoans. It is 2.5-6 m thick. The top consist of 30 cm thick lithified chalk with an incipient hard ground just below the boundary to the Lower Danian. The chalk is deposited in small asymmetric bryozoans-rich mounds with layers of flint nodules.

Danian

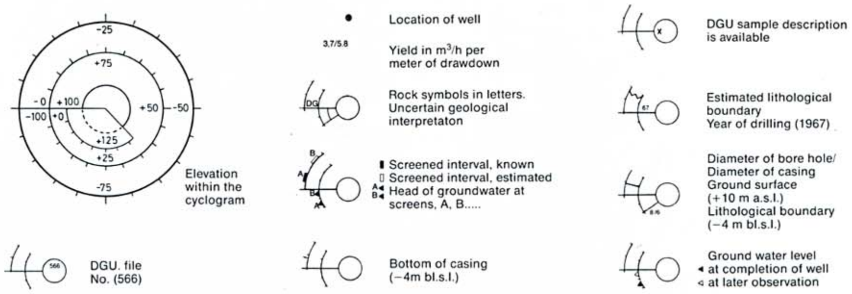
The Danian consists of several sediment types: 1. The Fiskeler (Rødvig Formation, Fiskeler Member), 2. The Cerithium Limestone (Rødvig Formation, Cerithium Limestone Member) 3. The Bryozoan Limestone (Stevns Klint Formationen, Korsnæb Member).

The Fiskeler is a 5-10 cm thick unit of black clay subdivided in several smaller beds. The Fiskeler is deposited in small discontinuous basins on the top of the Maastrictian chalk between the tops of the mounds (Fig. 42). The Cerithium Limestone is a 30-60 cm thick micritic strongly burrowed layer with flint layers and pyrite. The limestone overlies the Fiskeler and the Maastrictian chalk on the top of the mounds.

The bryozoan limestone is between 15 m and 25 m thick in the area. It is a white bryozoans-rich limestone deposited in asymmetric mounds with discontinuous layers of nodules of flint. Some hard grounds occur.

In the many boreholes from which only ditch samples have been available it can be difficult to find the boundaries between the units: Chalk-bryozoan and chalk-bryozoan limestone. The Fiskeler and Cerithium limestone only occur very seldom in the boreholes (Fig. 41).

LEGEND



ROCK LETTER SYMBOLS

B	Dug well
BK	Danian bryozoan limestone
C	Brown coal
DG	Glacial melt-water gravel
DI	Glacial melt-water silt
DL	Glacial melt-water clay
DS	Glacial melt-water sand
DV	Alternating thin melt-water beds
FS	Post-glacial fresh-water sand
G	Gravel, sand and gravel
GC	Miocene brown coal
GI	Oligocene – Miocene mica silt
GL	Oligocene – Miocene mica clay
GS	Oligocene – Miocene mica sand
GV	Oligocene – Miocene alternating thin beds
HI	Postglacial salt-water silt
HL	Postglacial salt-water clay
HP	Postglacial salt-water gyttja
HS	Postglacial salt-water sand
HV	Postglacial thin salt-water beds
I	Silt
ID	Interglacial diatomite
IL	Interglacial fresh-water clay
IP	Interglacial fresh-water gyttja
IS	Interglacial fresh-water sand
KG	Miocene quartz gravel
KS	Miocene quartz sand
L	Clay, marl
LL	Eocene Clay, plastic clay
M	Mull
MG	Glacial gravelly till
ML	Glacial clayey till
O	Fill, waste
P	Gyttja
PL	Paleocene clay
PV	Alternating thin Paleocene beds
S	Sand
SL	Eocene marl
U	Clay, sand and gravel
V	Alternating thin beds
X	No information

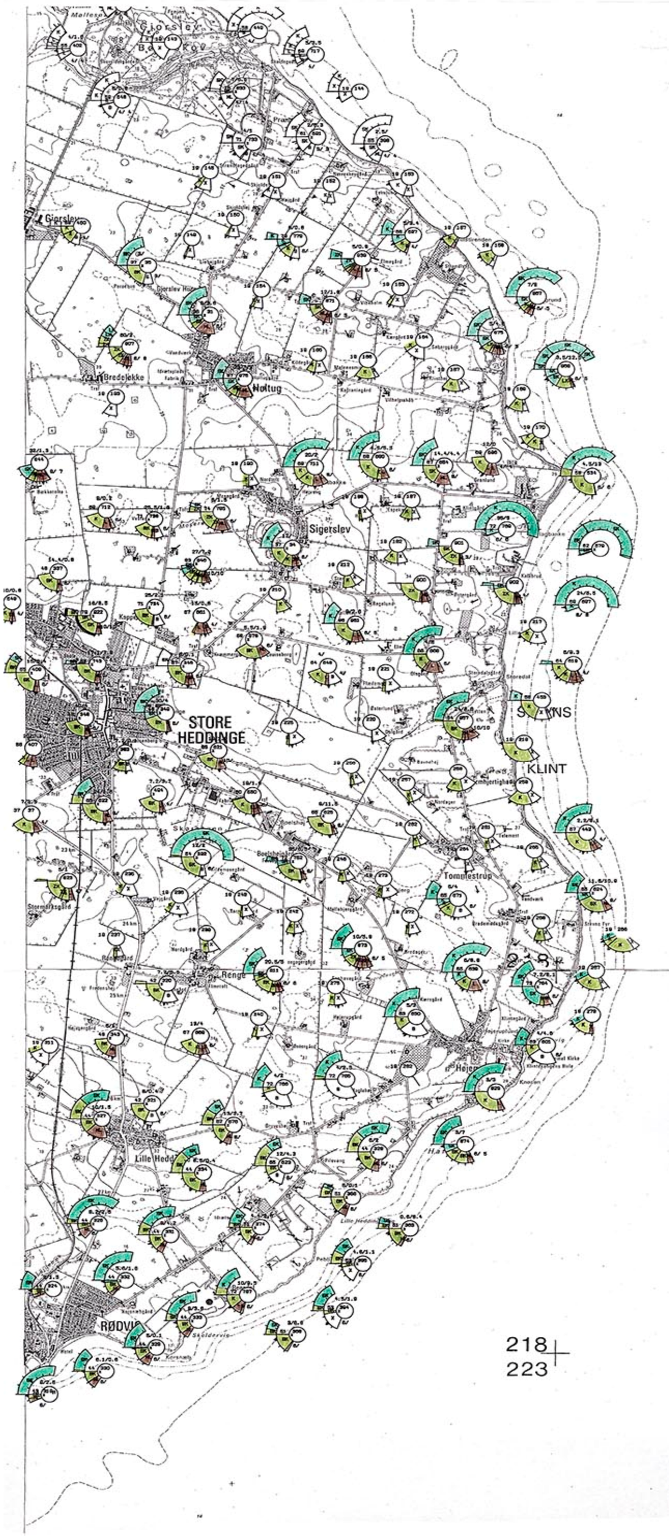
LITHOLOGY (interpretation)

- Post-glacial fresh-water sand, -gravel
- Post-glacial salt-water sand, -gravel
- Post-glacial salt-water clay, -silt, -gyttja, -peat, -alternating beds
- Late-glacial fresh-water sand, -gravel
- Late-glacial fresh-water clay, -gyttja, -peat, -alternating beds
- Glacial melt-water sand, -gravel
- Glacial melt-water silt
- Glacial melt-water clay, alternating beds
- Glacial Clayey till
- Interglacial fresh-water sand, -gravel
- Interglacial fresh-water clay, -silt, -gyttja, -peat, -diatomite, alternating beds
- Oligocene - Miocene sand, gravel, sandstone
- Oligocene - Miocene clay, silt, brown coal, alternating beds
- Paleocene - Eocene clay, silt, diatomite, volcanic ash
- Danian limestone

GEOLOGICAL SURVEY OF DENMARK NOVEMBER 1988

Andersen L. J. & Gravesen P., 1988

a.



b.

Figure 38. Geological Basic Data Map. a. Legend to the map (From Andersen & Gravesen, 1989). The dark green colour show Maastrichtian Chalk. b. The map shows the distribution and thickness of the Maastrichtian, Danian and Quaternary units. Scale 1:25.000.

A.

B.

Figure 42. A. The cliff Stevns Klint north of Højerup. B. The overhang marks the M-T boundary where thin layers of the Fiskeler can be seen in shallow basins.

6.5.2 Quaternary deposits

The Quaternary sediments in the area are totally dominated by clayey till which is between 1 m and 15 m thick, often thinnest in the coastal area (Figs. 37 and 43). The area consist of a weakly undulating moraine plain with only few low-lying parts (Figs. 44 and 45).

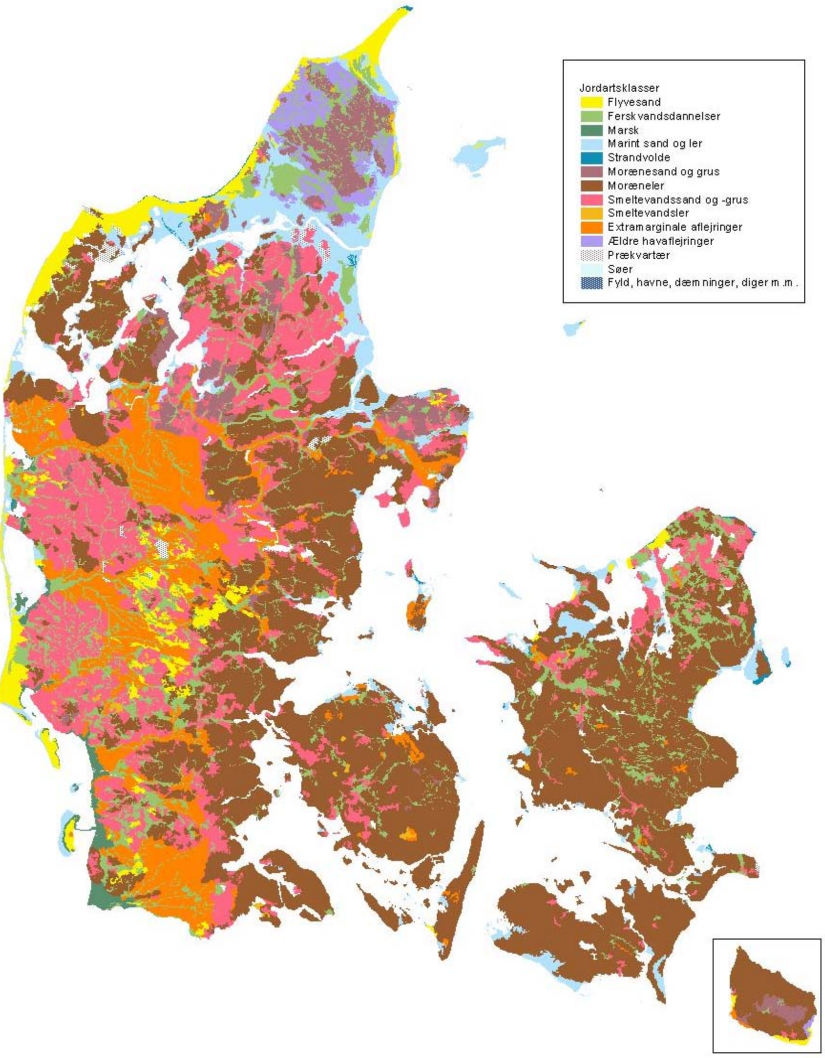


Figure 40. The map of the Quaternary surface deposits. Original scale: 1:200.000. Legend: Brown: Clayey till, light brown: Sandy till, red: Meltwater sand and gravel, orange: Sandur sand and gravel, purple: Late glacial marine deposits, light blue: Holocene marine deposits. Green: Holocene freshwater deposits, yellow: Aeolian sand (From Pedersen, 1989).

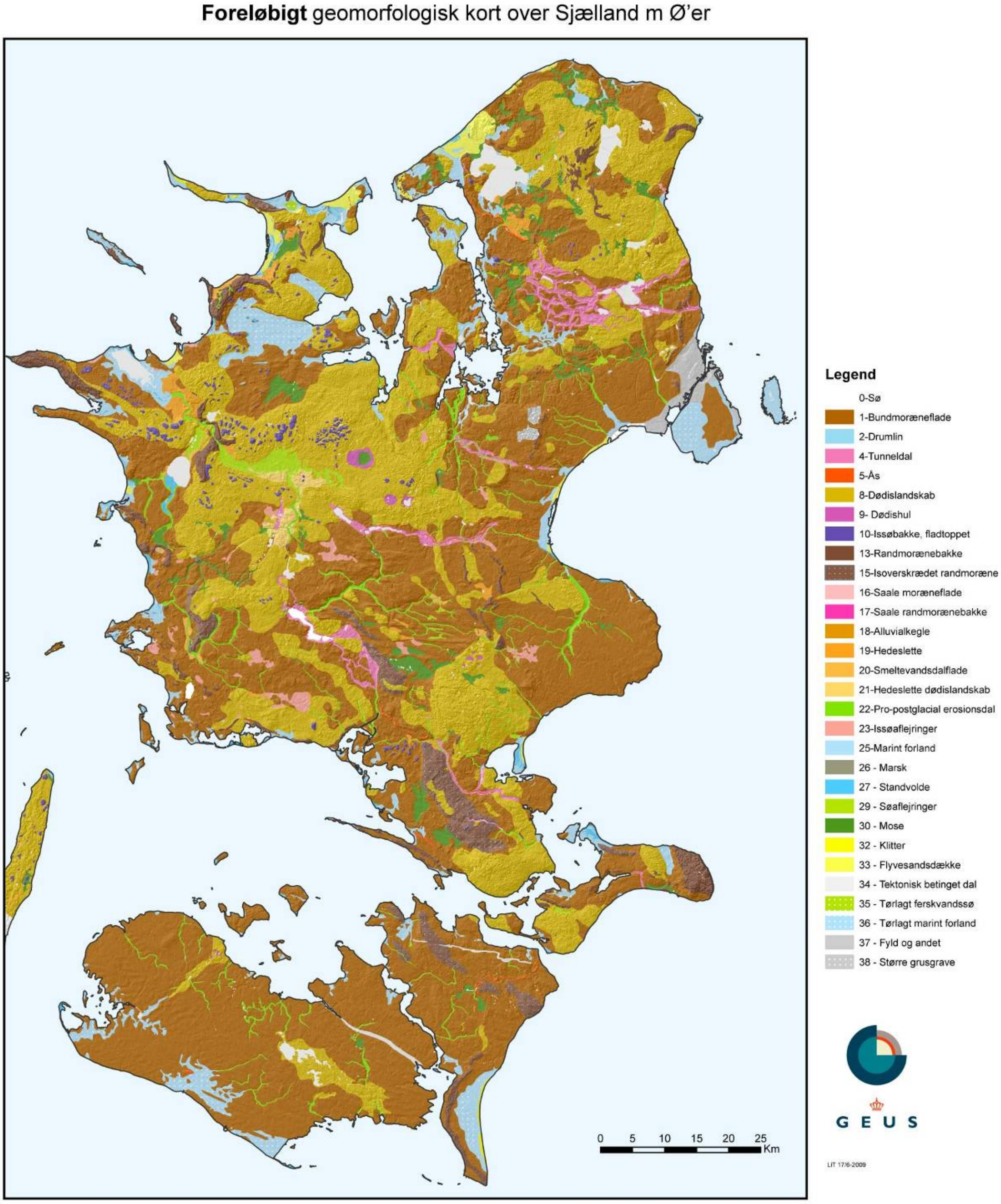


Figure 44. Geomorphologic map of eastern Denmark. Original scale 1:200.000. Legend for the important unit in the area: Brown: Clayey till plain (Jakobsen in prep.).

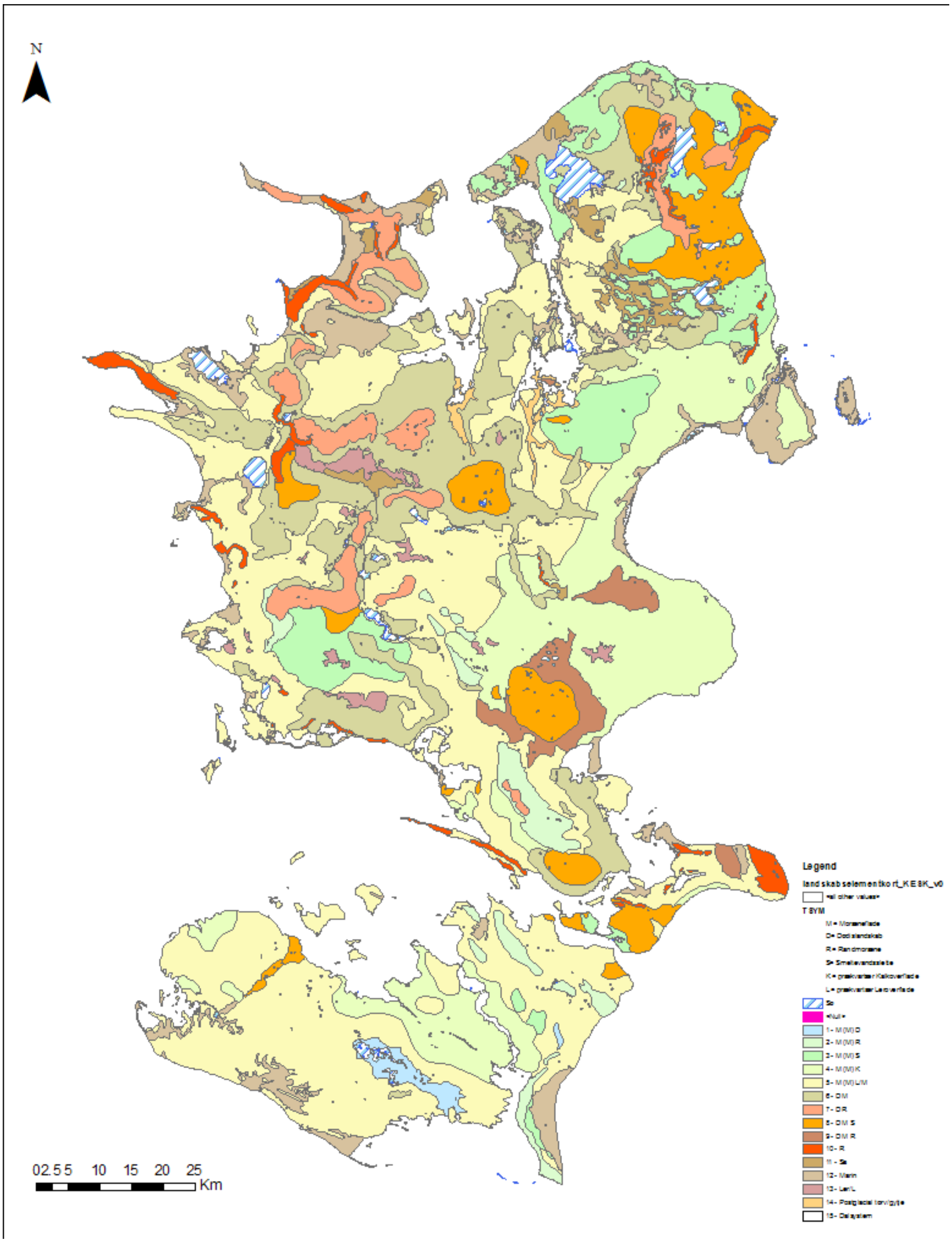


Figure 45. Poly-geomorphologic map of eastern Denmark. Digital map. Legend of the important unit in the area: Clayey till plain over limestone (Klint in Gravesen & Rosenberg, 2009).

The clayey till is silty, sandy with some gravel, olive gray and calcareous but in some parts of the area the upper 1-1.5 m is yellow brown and non-calcareous. The till contains thin sand lenses or layers and modelling of information from Højstrup demonstrates an abundant sand pattern (Fig. 46).

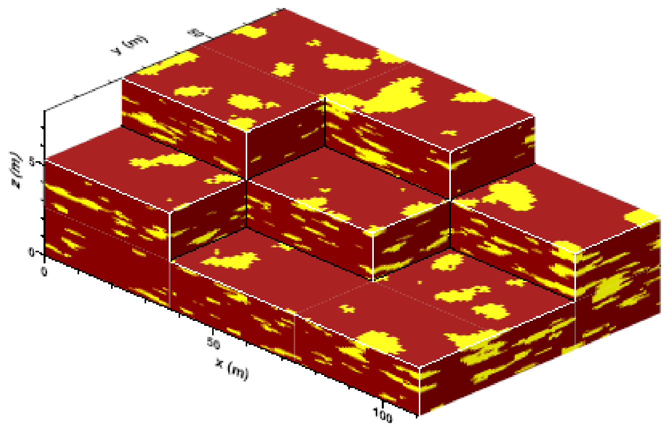


Figure 46. Geostatistic model for the distribution of sand lenses (yellow) in clayey till (Brown) at Højstrup (From Pedersen, 2004).

Grain size analyses of clayey till from Højstrup show the following: The matrix has 15 % in the clay fraction, approx. 30 % in the silt fraction and the rest is sand with a little gravel. At Gjorslev, also located just outside the area, the same conditions are found. At Sigerslev, the clayey till is up to 8 m thick and mainly yellow brown to olive brown (Figs. 47 and 48).

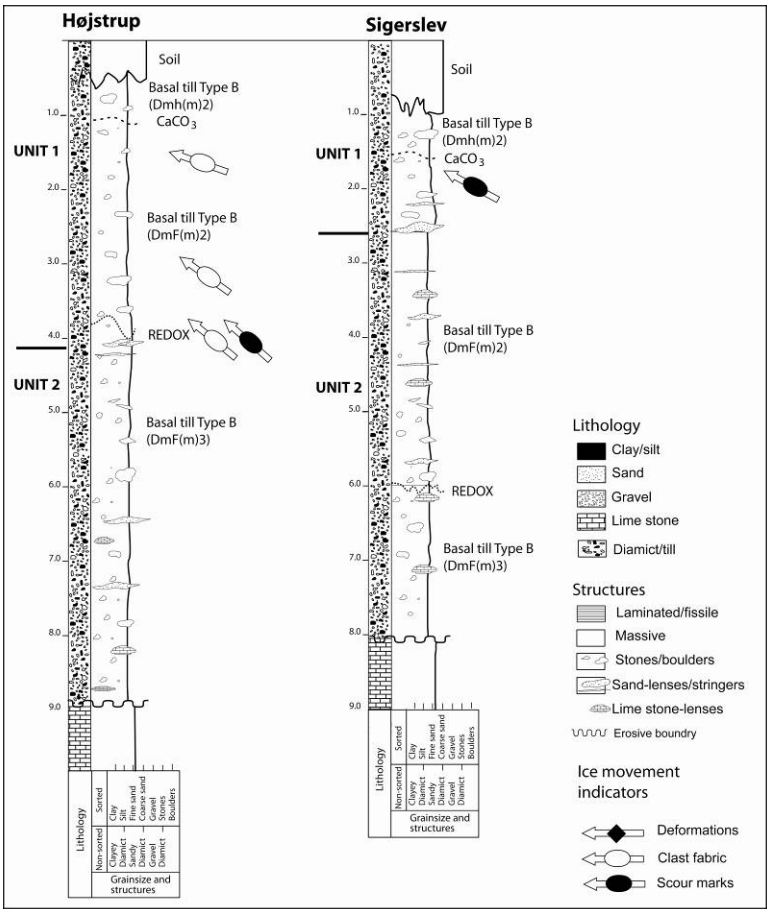


Figure 47. Lithological logs from Sigerslev and Højstrup locations (Nilsson et al, 2011, in prep).

Figure 48. Section in the Young Baltic clayey till (Approx. 8 m) at Sigerslev situated above the Maastrichtian chalk. (Photo: K.E.S. Klint).

Figure 49. Large irregular flint nodule in the chalk. The flint is located in a horizontal fracture zone. Stevns Klint cliff. The iron staining indicates the water flow in the fractures.

6.6 Tectonics, structures and seismic activity

6.6.1 Major tectonic structures

The elevation of the boundary between the Maastrichtian chalks and the Danian limestones is undulating through the 12 km long and up to 41 m high cliff Stevns Klint. This variation is demonstrated by the Upper Maastrichtian incipient hardground and Lower Danian erosional unconformity which follow each other almost parallel through the cliff. From Rødvig, the boundary is decreasing to down under sea level but from Peblingerenden, the boundary is increasing towards Sigerslev reaching the highest point. From there, the level of the boundary is decreasing towards Kulstirenden. At Storedal and Sigerslev, the Danian is eroded by Quaternary glaciers.

The weakly undulation of the deposits has been interpreted as a folding of the deposit after lower Danian time. Recently, offshore seismic investigations have shown that the wavy relief of the Lower Danian hardground at the base of the Stevns Klint Formation has amplitude of about 40 m. The culminations and depressions are representing the original seafloor topography. The topographic features comprise a large WNW-ESE trending valley bordered by a ridge.

The closest largest fault lines are the Carlsberg Fault to the east and the Roskilde Fault to the west. Dextral displacements along these faults delineating the tectonic Stevns Bloc should have been responsible for the formation of the vertical and horizontal fractures (shear fractures, extensional fractures and stress release fractures).

It seems possible to use the structural model from the Sigerslev chalk pit for the whole Stevns area including the fracture network described below.

6.6.2 Fractures

Fractures in the Maastrichtian chalk

Fractures in the Maastrichtian chalk have been investigated in some of the pits and can been recognized in the cliff. In the Sigersted chalk pit, one horizontal and four vertical fracture systems are recognized. Just below the Quaternary tills the chalk is crushed and heavily fractured down to 9 m. The horizontal fractures are uniform and the spacing increase from 20 cm at 20 m above sea level to 40 cm at 20 m below sea level. Normally, the horizontal fractures are more than 20 m long and pass through the flint layers. When horizontal fractures intersect the four vertical fracture systems, water is seeping out (Figs. 49 and 50).

Figure 50. Crossing vertical and horizontal fractures in the white chalk. A weak yellow staining around the fractures indicates water flow. Stevns Klint cliff.

<u>*Fractures in the Danian limestones*</u>
Fractures in the Danian limestones can be seen in the old Holtug pit and in the cliff.

<u>*Fractures in clayey tills*</u>
The clayey till is cut by fractures and other macropores and investigation in excavations at Højstrup and Gjorslev (just outside the area) have given the following picture (Fig. 51):

Rootless and earth worm burrows are found down to 1-1.4 m and the concentration in 75 cm depth is 300-500 per m^2. These macropores are decreasing downwards.

From the ground surface and down to approx. 2 m depth, freeze-thaw fractures occur. Two fractures systems dominate. One system is vertical and subvertical fractures reaching down to 4-5 m below ground surface and one system of subhorisontal fractures situated 1.8 to 2.3 m below ground surface. The redox interface varies between 3.5 m and 4 m.

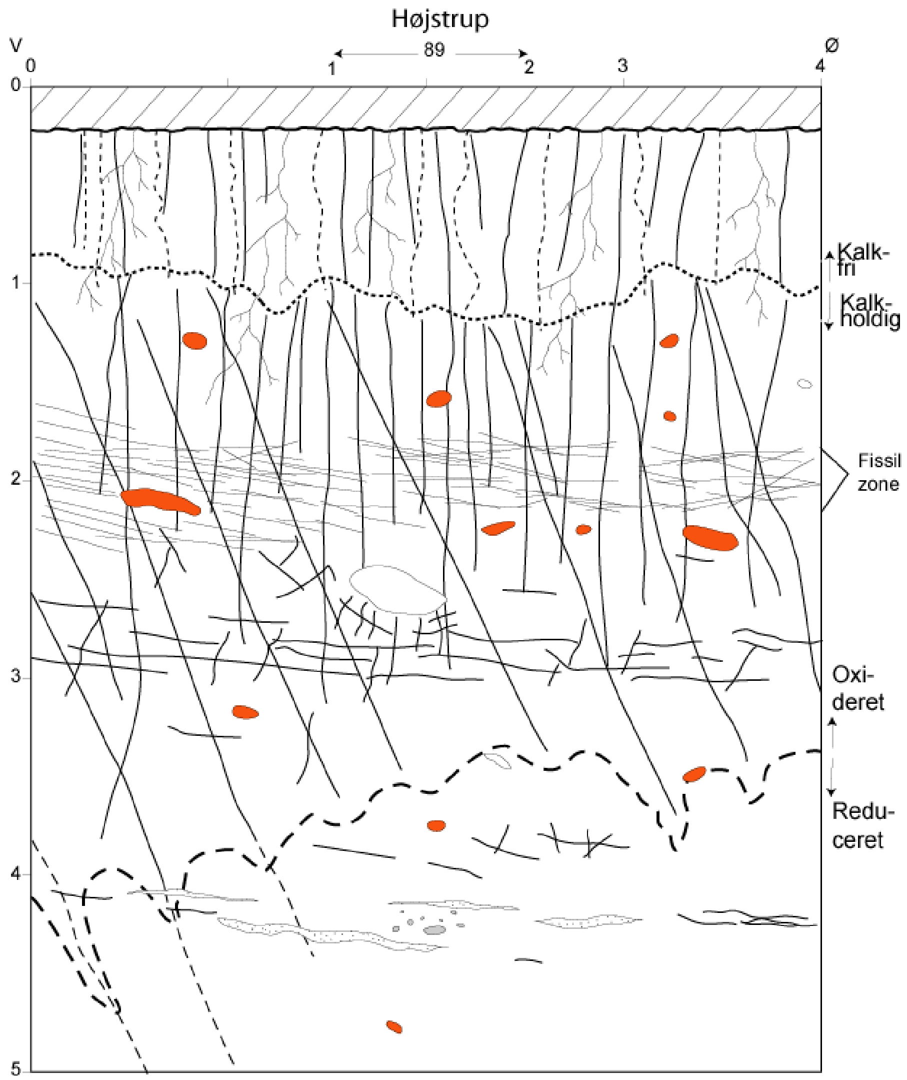


Figure 51. Section from the upper 5 m at Højstrup. Vertical, subvertical and horizontal fractures cut the clayey till.

Shallow boreholes at Højstrup (DGU no. 218.1876,. 1890,.1891,.1892,.1893) contain floes of limestone-chalk in the tills and isolated meltwater clay which point out that glaciotectonic disturbances have occurred (Fig. 52).

At Sigerslev, chalk floes and sand lenses also occur in the till (See Fig. 47).

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BORERAPPORT — **DGU arkivnr: 218. 1892**

Borested : Vissemosevej 20, Gevnø
4673 Rødvig Stevns
KUPA projekt. Ingen borerapport, Højstrup IV

Kommune : Stevns
Region : Sjælland

Boringsdato : 15/10 2002 — **Boringsdybde** : 8.2 meter — **Terrænkote** : 10.27 meter o. DNN

Brøndborer : Thomas Brøker, Holbæk
MOB-nr :
BB-journr :
BB-bornr : 4

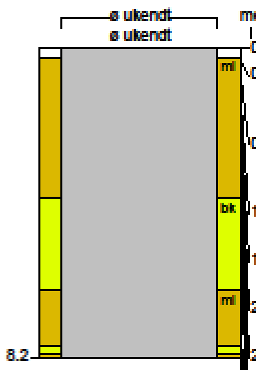
Prøver
- **modtaget** : 16/10 2002 **antal** : 13
- **beskrevet** : 11/3 2003 **af** : TC
- **antal gemt** : 0

Formål : Undersøg./videnskab
Anvendelse : Sløjfet/opgivet bor
Boremetode :

Kortblad : 1512 ISV
UTM-zone : 32
UTM-koord. : 711765, 6128708

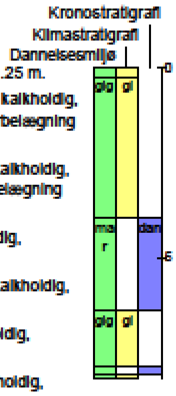
Datum : ED50
Koordinatkilde : GEUS
Koordinatmetode : GPS

Notater : Bill Harrar var projektleder



meter u.t.

0 MULD, leret, mørk gråbrun, kalkfri. (muld). Laggrænse skønnet. Prøve udtaget ved .25 m.
0.25 LER, sandet, svagt siltet, svagt gruset, lys olivenbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved .5 m. Note: mange okkerbelægning langs sprækker.
0.5 LER, sandet, svagt siltet, svagt gruset, lys olivenbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 1 m. Note: mange okkerbelægning langs sprækker.
1 LER, sandet, svagt siltet, svagt gruset, olivengrå, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 1.5 m.
1.5 LER, sandet, svagt siltet, svagt gruset, lys olivenbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 2 m.
2 LER, sandet, svagt siltet, svagt gruset, olivenbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 2.5 m. Note: 1 sten.
2.5 LER, sandet, svagt siltet, svagt gruset, olivenbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 3 m.
3 LER, sandet, svagt siltet, svagt gruset, mørk gråbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 3.5 m.
3.5 LER, sandet, siltet, svagt gruset, mørk gråbrun, svagt indh.af kalkklaster, kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 4 m. Note: få sprækker.
4 KALK/KRIDT, blød, slammet, svagt leret, lys grå, bryozoer, "bryozokalk". Laggrænse skønnet. Prøve udtaget ved 6.4 m.
6.4 LER, sandet, siltet, svagt gruset, olivengrå, stærkt kalkholdig, "moræneler". Laggrænse skønnet. Prøve udtaget ved 7.9 m. Note: 1 sten.
7.9 KALK/KRIDT, blød, slammet, svagt leret, hvidgrå, bryozoer, "bryozokalk". Laggrænse skønnet. Prøve udtaget ved 8.1 m.
8.1 LER, klumper af kalk, olivengrå, stærkt kalkholdig, "lokalmoræneler". Prøve udtaget ved 8.2 m.



Aflejringsmiljø - Alder (klima-, krono-, litho-, biostratigrafi)

meter u.t.	
0 - 0.25	terrigen - postglacial
0.25 - 4	glacigen - glacial
4 - 6.4	marin - danien
6.4 - 7.9	glacigen - glacial
7.9 - 8.1	marin - danien
8.1 - 8.2	glacigen - glacial

Figure 52. Borehole log for DGU no. 218.1892 which show two chalk/limestone floes in the clayey till. Legend. BK: Danian Bryozoan limestone, ML: Clayey till.

6.6.3 Geological model

The Geological model for the area based on field localities and boreholes has three major components (Fig. 53):

A. Quaternary Clayey till. The clayey till covers almost all the limestone and chalk deposits in the area. It is between 1 m and 15 m thick. Thin sand lenses and floes of the pre-Quaternary deposits occur.

B. Danian Limestones reach a thickness of between 2 m and 25 m. The deposits include a series of different limestone types and thin clays.

C. Maastrichtian chalk is rather uniform in the area and it is at least 60 m thick.

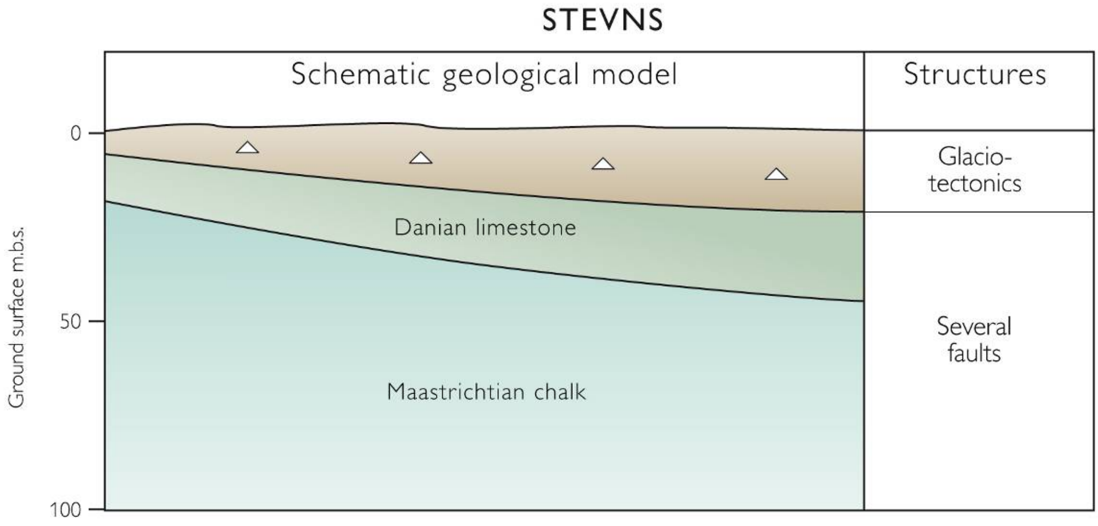


Figure 53. Schematic geological model for the area.

6.6.4 Earthquake activity

Seismic activity in the area

The seismic station net in Denmark is run by GEUS and comprises 5 stations of which three stations are located on Sjælland: Gilleleje museum, Vestvolden, København and Lille Linde, Stevns (GEUS´s homepage: www.geus.dk).

The earthquake activity is measured with respect to location, time and size. The activity in Denmark is very low compared to many other countries and during the period 1929-2003 only few earthquakes potentially related to the Stevns area´s geological structures occur (Fig. 54).

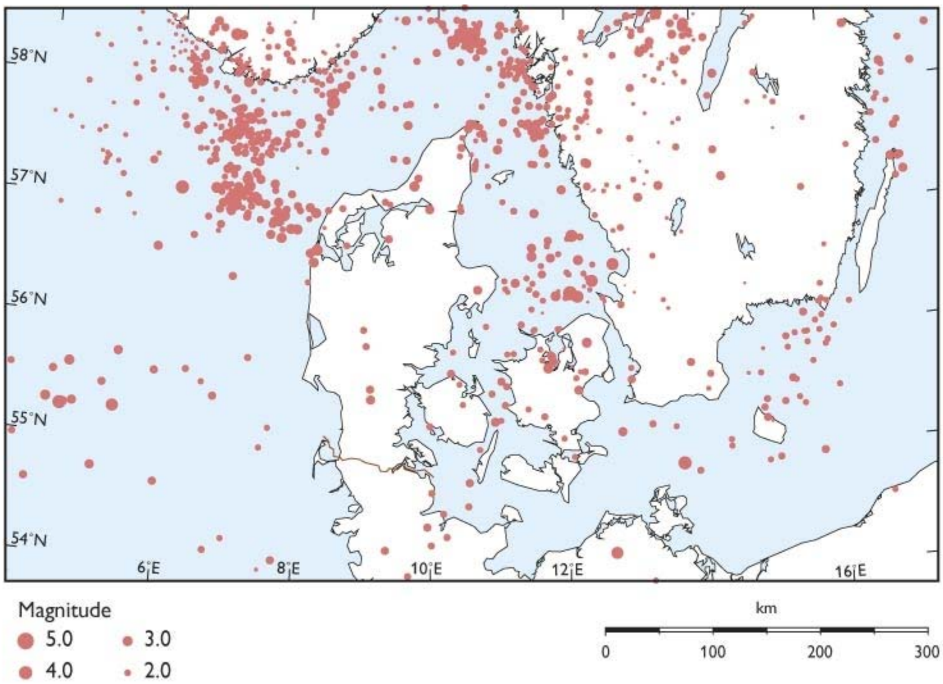


Figure 54. Earthquake epicenters in the Danish area (red dots). (Larsen et al., 2008).

Earthquake risk conditions in relation to subsurface movements
The seismic activity on larger depth is difficult to relate directly to the more near surface layers. The isostatic rise of the land area is a slow process while earth quakes are faster movements. The shown faults in the Cretaceous and Paleogene deposits can partly be traced to larger depth but not upwards to the ground surface.

Therefore, it is impossible to relate recent seismic activity to the many faults and fractures in the bedrocks. Other signs of recent movements along the faults and fractures have not been proven.

6.7 Ground stability

The ground stability of the area is regarded as very well.

6.8 Groundwater hydrogeology

6.8.1. Groundwater characteristics

In the Stevns area, the chalk is characterised by dual-porosity and a high porosity in the matrix domaine. Pronounced fracture systems dominate the flow mechanisms in the chalk by offering preferential flow paths for fluids. Permeability and porosity in the white chalk (Sigerslev Formation) have been measured to 45-50 % and less than 10 milli-Darcy (or < 10^{-8} m/s), respectively. The thin Rødvig Formation deposits have porosity values around 45 % and permeability from 10 to 20 mD. Finally, measurements in the lower 1 meter of the

Stevns Klint Formation show porosity values from 35 to 45% and a large range of permeability between 80 and 500 mD. Studies in the Sigerslev quarry focused on mapping and characterization of fracture networks in the same chalk formations where it was attempted to identify the larger-scale preferential flow paths using heat as tracer.

The clayey till cover has also dual porosity characteristics with a slow, but measurable, water movement in the porous matrix domain, compared to the faster macropore flow in fractures, porous lenses of sand or brecciated chalk (Figs. 55 and 56). Matrix permeability of clayey till typically ranges between 10^{-9} and 10^{-10} m/sec. Bulk hydraulic conductivity of fractures and matrix typically range between 10^{-5} and 10^{-7} m/sec.

The Stevns area east of Store Heddinge (Area 6) is situated in an area with one shallow groundwater body (DK2.4.1.1 of meltwater sand (Køge Sand)) covering the northern part of Stevns (Fig. 57). Two regional groundwater bodies are covering the northern part (DK2.4.2.1 or Køge Kalk) and the southern part (DK2.6.2.11), respectively. Both regional groundwater bodies consist of limestone/chalk (Fig. 58). Deep groundwater bodies have not been identified in or near Area 6 in the catchment management plan of the Ministry of Environment. The subdivision into groundwater bodies is described as part of the basis analysis (Part 2) carried out by the former Storstrøms Amt in 2006. The northern groundwater bodies of Stevns constitute the southernmost part of the catchment management plan "Hovedvandopland 2.4, Køge". The southern regional groundwater body covers the northernmost part of the catchment management plan "Hovedvandopland 2.6, Østersøen".

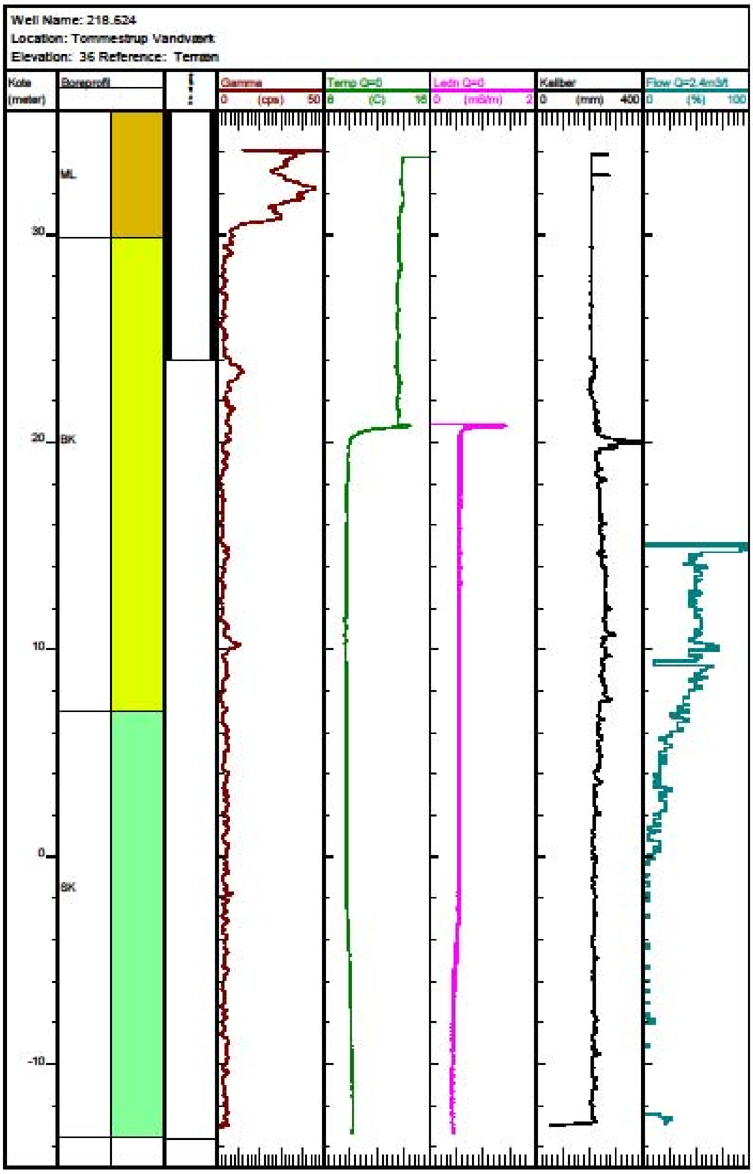


Figure 55. Physical logs from the borehole DGU No. 218.624, Tommestrup Water Work. The flow log marks fracture zones (horizontal or inclined) with inflow of water in elevation + 15 m and + 11 m. Apparently no inflow occurs below elevation 0 m.

Figure 56. Fractures in the chalk. Flowing water stains the chalk yellow and occasionally it is possible to see the water flow directly.

The overall assessment of the chemical and quantitative status of the shallow and regional groundwater bodies (DK2.4.1.1) and (DK2.4.2.1) have resulted in a poor status of both the groundwater quantity and quality (see Section 6.9). The poor quantitative status of DK2.4.2.1 is due to the fact that the actual groundwater abstraction in the area and model simulations indicate that a sustainable groundwater abstraction in the regional groundwater body will exceed the 35 % - threshold of the groundwater recharge. The shallow groundwater body 2.4.1.1 has a poor quantitative status due to an over-exploitation of the groundwater resource. Thus, there are examples of streams that dry out in summertime. Finally, the regional groundwater body (DK2.6.2.11) has a good status of the groundwater quantity but a poor status of the water quality (see Section 6.9).

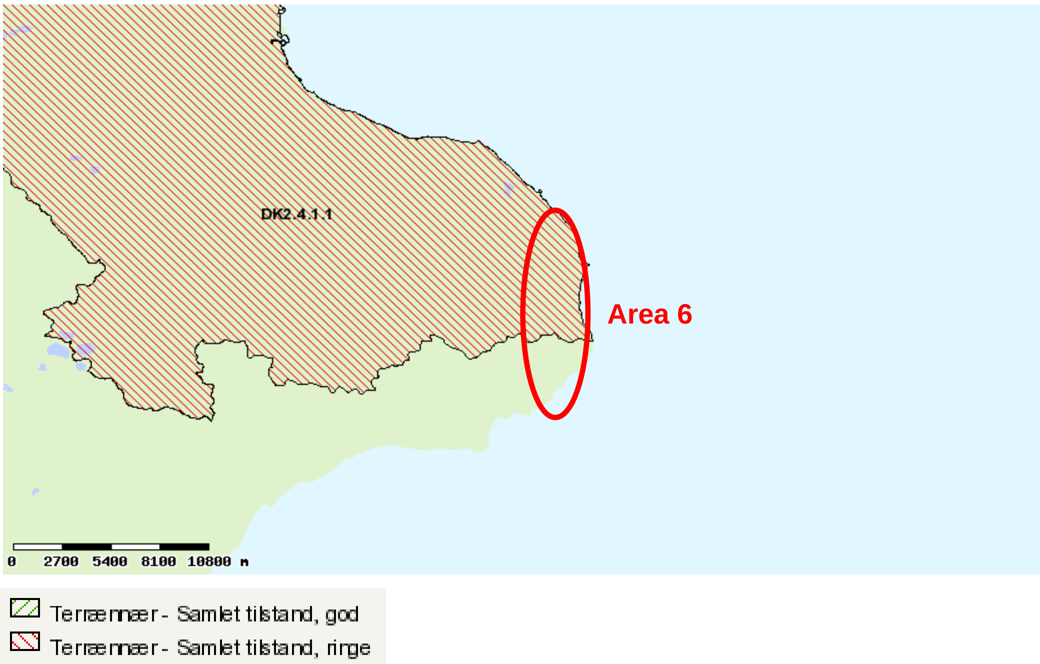


Figure 57 Shallow (or terrain near) groundwater body DK2.4.1.1 on northern side of Stevns. The overall assessment of chemical and quantitative status: poor status (Red shaded area) (From the Ministry of Environment, 2010b).

Figure 58. Regional groundwater bodies in Stevns area. The overall assessment of chemical and quantitative status: poor status (Red shaded area) in DK2.4.2.1 and DK2.6.2.11 (From the Ministry of Environment, 2010).

The chalks and limestones have dual porosity: Primary porosity in the matrix pores and secondary porosity in the fractures and other macropores. Due to the variable cementation of the sediments, the build up in mounds and the loading and push of the Quaternary glaciers, the groundwater conditions can be different from one area to another.

The clayey till cover also has dual porosity but the water movement in the matrix is very slow compared to the macropore transport (Figs. 55 and 56).

Three minor water supplies/Water works exist in or near the area, all located 200 to 500 m from the coastline. A typical water supply (Fig. 55) belongs to Tommestrup Water Work and the borehole yields 11.6 m^3/hr at 10.9 m draw down (DGU no. 218.624) . The groundwater, which flows into the well come from different levels, based on major fracture zones.

6.8.2 Drinking water areas

The groundwater has to be protected to ensure that our current and future need for clean drinking water can be met. It is the Environmental Centres (former counties) responsibility to do the planning, based on the two criteria: First, to make sure that the future necessary quantity of clean groundwater can be abstracted. Secondly, the groundwater aquifers must be protected against recent and future pollution.

As part of the Danish Government´s efforts to protect groundwater, the Environmental Centres have designated areas of major groundwater aquifers, so-called OSD-areas. OSD stands for "Areas of special drinking water interests” (Fig. 59).

The rest of the country is divided into "Areas with water interests" (OD-areas) where good sources of drinking water are also located and "Areas with limited drinking water interests", where it is difficult or impossible to obtain good groundwater quality because the water is more or less contaminated.

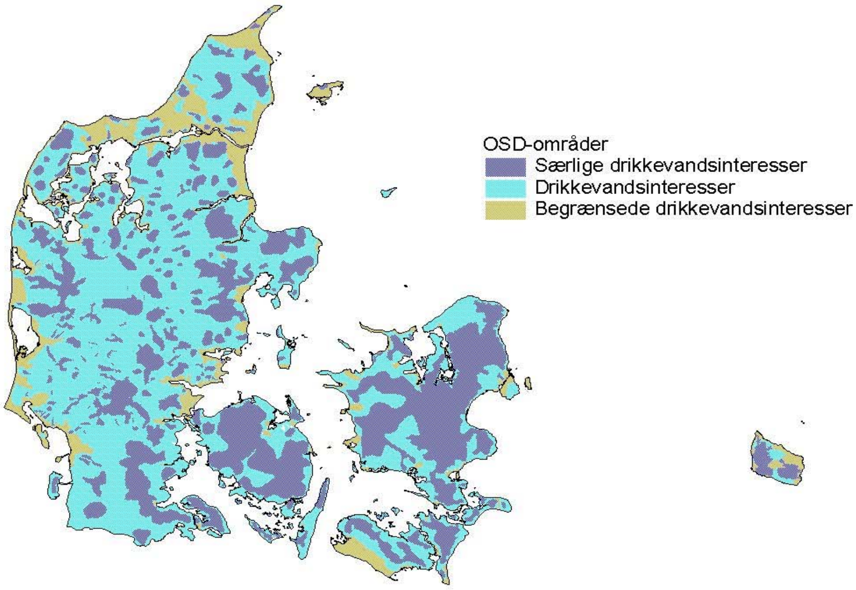


Figure 59. Map of three categories of drinking water interest in Denmark. The areas of special recharge groundwater and drinking water interests (OSD areas protected by law) are in dark blue colour. The areas shown with light blue colour are areas of some interest for drinking water purposes (OD areas). The areas in brown colour are areas of limited (or none) drinking water interests (http://kort.arealinfo.dk/).

The Stevns area is an area of some interest of drinking water purpose (OD) and some small Water Works are located near the small cities as e.g. Store Heddinge. The different drinking water areas in the Stevns region are shown in Fig. 60. Most of the central part of Stevns is categorised as an area with special drinking water interest. There is a 1-2 km wide zone along the coastline with some drinking water interest. There are limited drinking water interests right at the coast shore. The available area for a potential waste disposal site is limited to the outermost kilometre of Stevns. It is important to notice that 4-5 minor water works are situated south of Sigerslev quarry along the coast, positioned at a distance of less than 1 km from the coastline. In addition, several abstraction wells exist for households and irrigation of crops in the same coast near zone.

Figure 60. Various drinking water areas situated in the Stevns area. Dark Blue: Areas of special drinking water interests; Light blue: Areas of some drinking water interests; Yellow: Areas with limited or none drinking water interests (http://kort.arealinfo.dk/).

6.9 Groundwater chemistry

The chemical status is poor in all three groundwater bodies situated within the Stevns area East of Store Heddinge (Area 6). The water quality in DK2.6.2.11 is poor due contents of nickel that exceed acceptable limits in groundwater. Findings of pesticides and chlorinated solvents in DK2.4.1.1 and DK2.4.2.1 have resulted in the poor chemical status of these two groundwater bodies. In addition, salt water intrusion due to over-exploitation of the coast near groundwater resource is a severe problem along Køge Bugt, but less important along the Stevns coastline.

The chemical status is poor in all three groundwater bodies that are situated within the Stevns area East of Store Heddinge (Area 6). The water quality in DK2.6.2.11 is poor due contents of nickel that exceed acceptable limits in groundwater. Findings of pesticides and chlorinated solvents in DK2.4.1.1 and DK2.4.2.1 have resulted in the poor chemical status of these two groundwater bodies. In addition, sea water intrusion due to over-exploitation of groundwater in the limestone aquifers along Køge Bugt is a severe problem, but of less importance along the Stevns coastline. Two deep research wells, Stevns 1 (north coast of Stevns) and Stevns 2 (southern coast stretch) have identified the salt/freshwater transition at 75 m and 40 m below sea level, respectively.

6.10 Climate and climate changes

The actual climate and the expected future climate changes and sea level development is described in Gravesen et al. (2010, Rep. No. 2). It is not expected that a rise in net precipitation will influence on (deep) groundwater recharge and level. It is obvious, that a higher sea level and any raise in storm activity may increase the ongoing coastal erosion.

6.11 Restrictions and limitations

Within the area, the chalk is dug in one pit: Sigerslev (Fig. 61). Besides this pit, the area close to the shore is classified as an area of raw material interest. New permission for excavation of chalk will only be given in already designated raw material areas.

No restrictions regarding NATURA2000 habitats or areas protected by Naturbeskyttelsesloven (law for nature protection) within Area 5. However, the coastline along Stevns is registered as NATURA2000 habitat area. Severe raw material interests appear in the Sigerslev quarry and Stevns Cliff profiles are listed as a potential UNESCO World Heritage location. Sea water intrusion can potentially be a problem if sea level rises due to climate changes, or if an over-exploitation of the limestone aquifers happens in future at Stevns.

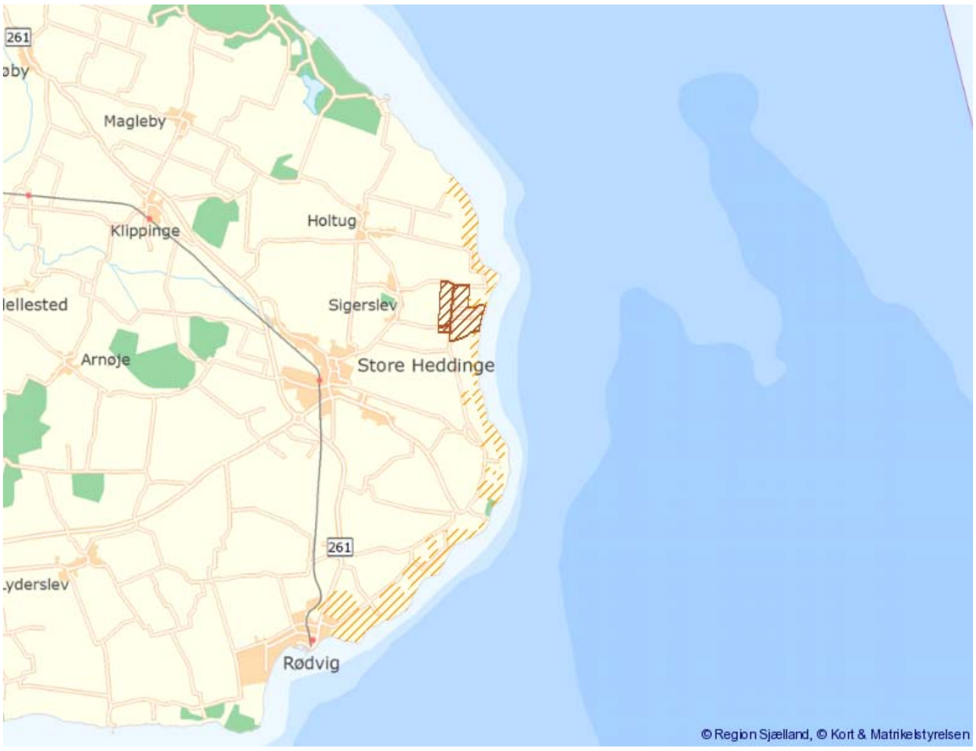


Figure 61. Areas of raw material (chalk) excavation (red brown) and areas of raw material interests (yellow) (From Region Sjælland, 2008).

Natura 2000 areas are located in the Baltic Sea close to the coast of Stevns (Fig. 62).

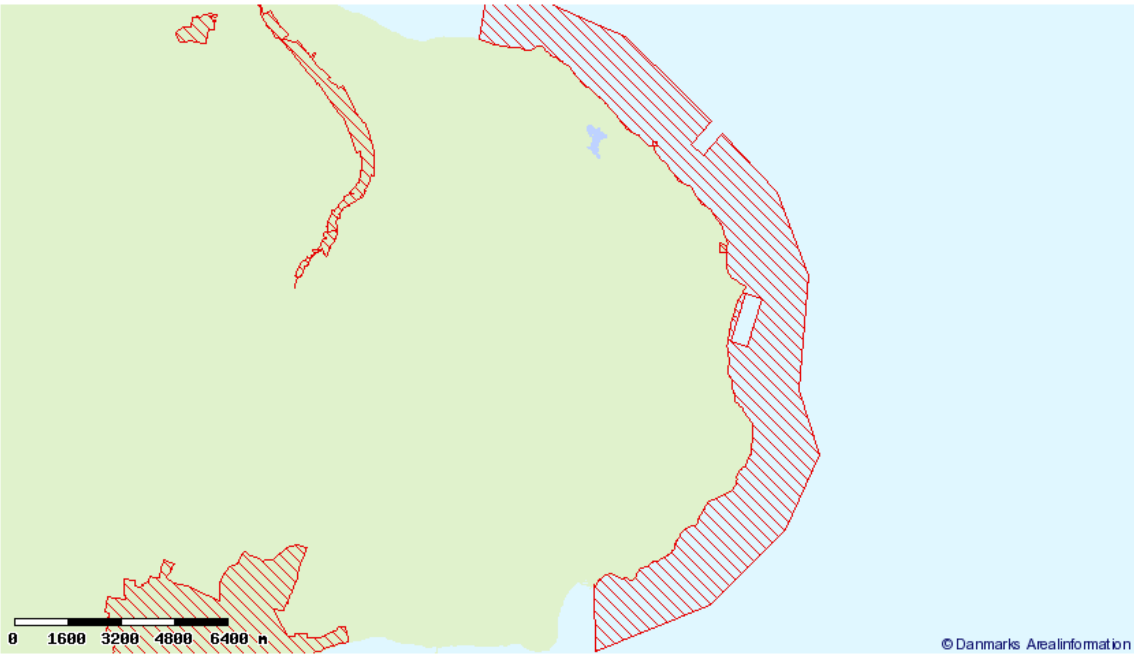


Figure 62. NATURA2000 areas along the coast of Stevns (http://kort.arealinfo.dk/).

6.12 Summary of the area conditions

Amount of data:
General many shallow wells and field data from the cliff and the raw material pits. No geophysical and chemical data.

Homogeneous conditions and isolation of the waste by low, permeability layers:
Relatively homogeneous conditions in the Quaternary deposits down to approx. 15 m. However, 15 m of glacial till materials are not expected to have a satisfying protective capability. Information about the deep limestone and chalk layers and the fracture system can partly be described and it is obvious that some factures are water filled and transport water. The fracture problems have to be considered in relation to other sites. A special problem is the occurrence of hardgrounds.

Stability
Good stability on surface and depth

Seismic activity and tectonic movements
Fault zones are bordering the area and they are also known outside the area with regional importance. The faults are seen in the pre-Quaternary deposits but are not demonstrated in the Quaternary layers. Seismic activity is measured relatively close to the fault zones but it is not possible to describe the present importance and problems.

Groundwater conditions

The artesian groundwater reservoir conditions in the deposits are related to the Maastrichtian chalk and Danian limestone reservoirs and the Quaternary cover. The groundwater flow is directed towards east into the Baltic Sea. The distance is short.

Dilution of pollution and retention of pollution

No Danish studies have been carried to document dilution capabilities or retension of radionucliides in glacial till or limestone materials.

Drinking water interests

The area is partly an OD area and partly an area with limited interests. Only minor local water supplies occur, and they are especially for the smaller cities.

Groundwater chemistry, non-aggressive components

The groundwater contains apparently no aggressive components but saltwater intrusion could be a future problem.

Ground surface conditions

Processes on the ground surface should not give problems on a disposal.

Climate extreme conditions and sea level rise

Climate changes, storm and heavy precipitation extremes and future sea level rise will have some influence on the area. Erosion of the coastal cliff will possibly increase.

Other restrictions

No other restrictions will probably give problems.

6.13 Final remarks

Despite the quality of the chalk and limestone as groundwater reservoirs, the area is chosen as a potential disposal area. The main reasons are pointed out above where also the negative characteristics are mentioned. Finally, it is obvious to address that the Ministry of Defence has had a system of tunnels and caverns in the limestone deposits close to the coast between Rødvig and Højerup (Koldkrigsfortet)(Fig. 63). The tunnels and caverns are situated 18 m below ground surface and have a length of 1.6 km. This underground military fortress has functioned for many years as a working area for more than 168 persons at the same time. This is now a museum. Other dug caverns in the Danian limestones are situated in northern Jylland and northern Sjælland, often down to larger depths.

Figure 63. Tunnels in the Fortress of Stevns dug into Danian Bryozoan Limestone (From www.stevnsfortet.dk).

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The specific maps and wells will be cited in the reports describing the approx. 20 localities.