DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/123

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report no. 2

Characterization of low permeable and fractured sediments and rocks in Denmark

Peter Gravesen, Bertel Nilsson,
Stig A. Schack Pedersen,
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& Troels Laier

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MINISTRY OF CLIMATE AND ENERGY

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1. INTRODUCTION

The low and intermediate level radioactive waste from Risø (the nuclear reactor buildings plus different types of material from the research periods) and radioactive 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 low permeable sediments or rocks that can isolate the radioactive waste from the surrounding deposits, groundwater resources, and recipients from human activities. The sediments or rocks shall also act as protection, if the waste disposal leaks radioactive material to the surroundings. This goal can be reached by use of sediments or rocks characterized by low water flow potentials and high sorption potential.
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).

In Denmark, many different kinds of fine-grained sediments and crystalline rocks occur from the ground surface down to 300 meters depth. Therefore, the possible geological situations include sediments and rocks of different composition and age. These situations are geographical distributed over large areas of Denmark. In the following chapters, these sediments and rocks are shortly described based on existing information and include five different major types of sediments and rocks: 1: Crystalline granite and gneiss of Bornholm (because these rock types are host for waste disposals in many other countries). 2: Sandstone and shale from Bornholm (as these sediments are relatively homogeneous although they have fracture permeability). 3: Chalk and limestone (because these sediments may act as low permeable seals, but in most areas they 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: Quaternary glacial, interglacial and Holocene clay deposits. These sediments are distributed all over Denmark.

All Danish sand and gravel deposits are excluded from the description owing to their potential as groundwater reservoirs, their high permeability, low sorption possibilities and low protection qualities 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. Therefore, in certain situations, it may be necessary to include sand and gravel sediments in the final descriptions.
This report is the second in the series: Low - and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report No.2.

2. PRE-QUATERNARY AND QUATERNARY DEPOSITS AND ROCKS

The following chapters describe the low permeable and fractured deposits and rocks in relation to their lithology, thickness and distribution. Also existing knowledge and data on hydraulic parameters, mineralogy and chemistry are included (Gravesen et al., 2010). All pre-Quaternary deposits and rocks are described under their formal or informal names while the Quaternary deposits are described under sediment/depositional environment types. A chart of the geologic time scale is seen in Fig. 2.
A literature list is included with reference to the used papers, reports, books, maps and databases. The list is not total comprehensive and for further reading, it is possible to find more references in the cited literature. The distribution of the sediments and rocks is seen in Figs. 4, 5 and 7.

Figure 1. Red, calcareous, very fine-grained, sticky, plastic marine clay with microfossils (Røsnæs Clay Formation) at Albæk Hoved, Jylland.

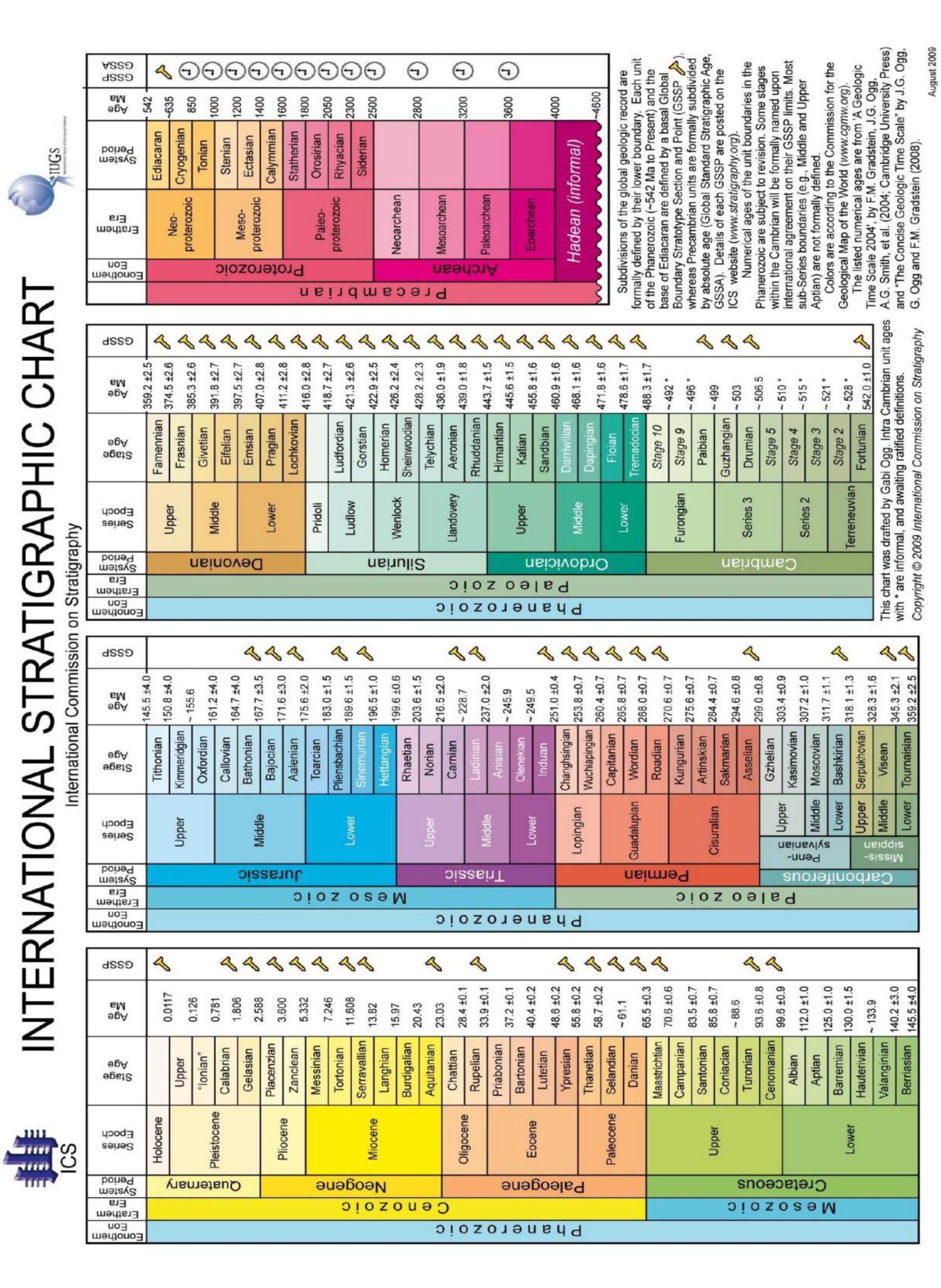


Figure 2. Chart of the global geologic time scale (Copyright 2009 International Commission on Stratigraphy).

Figure 3. Quarry with strongly fractured granite in Bornholm.

3. PRECAMBRIAN CRYSTALLINE BASEMENT ROCKS

The distribution of the different types of basement rocks on Bornholm is seen in Fig. 4. (VARV, 1977).

All granites, gneisses and migmatites are cut by horizontal and vertical fractures often at least down to the depth of the quarries (80 m), but borehole information points to fractures and weathered rocks at larger depth. The fractures and larger faults are oriented east – west, north west- south east or north east- south west. Large fault bounded valleys (sprækkedale) in the basement rocks have the same orientations. More information is presented in Pedersen & Gravesen (2010). The rocks are also cut by veins and bodies of red grey, coarse-grained pegmatite, red grey fine- grained aplites and black very fine-grained diabases.

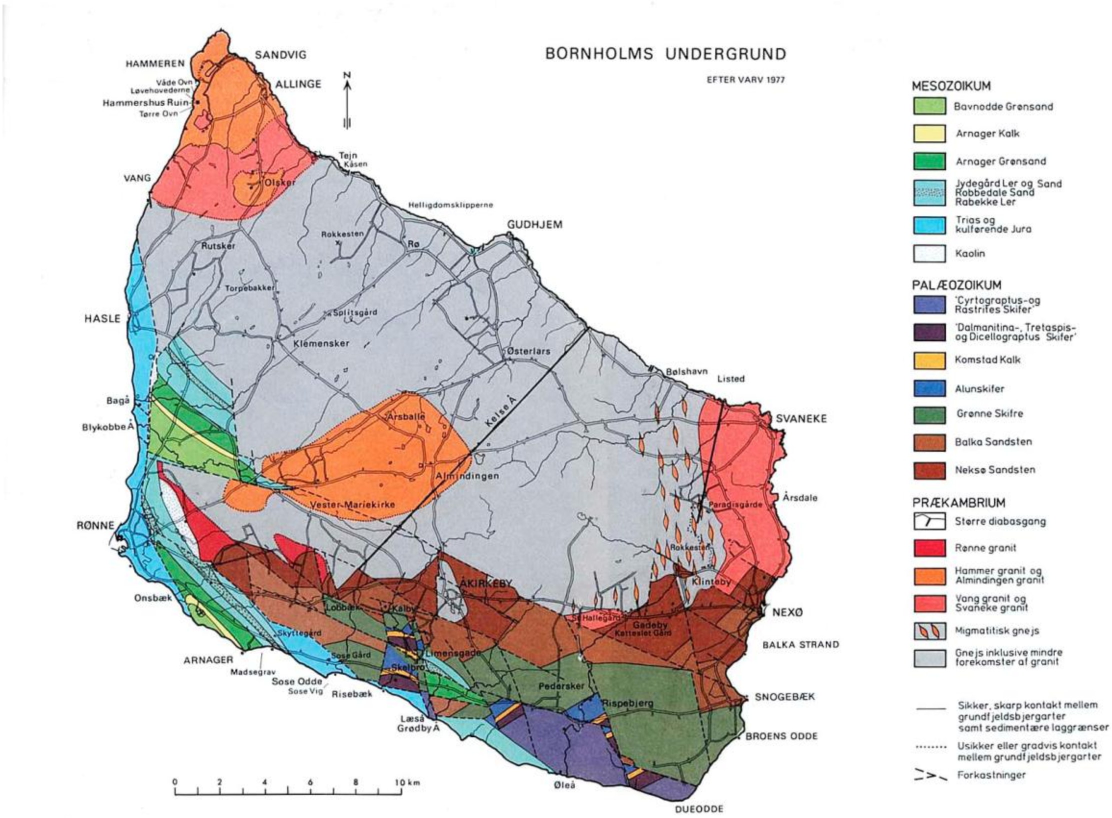


Figure 4. Map of the pre-Quaternary deposits and rocks of Bornholm (From VARV, 1977). Legend: Prækambrium: Precambrian (grey and red colours), Palæozoikum: Palaeozoic, Mesozoikum: Mesozoic.

3.1 Rønne Granite

Age: Precambrian

Localities: Southwest Bornholm. The granite is often exposed on the earth surface and few quarries shows deeper parts of the granite bodies. Few boreholes reach the granites.
Rock types: The Rønne Granite is dark grey or black medium-grained granite with a weak reddish colour. The granite is often weathered to kaolin and a large kaolin body is superimposed the granite northeast of Rønne.
Thickness: Very thick. The bottom is not known.
Distribution: Southwest Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.2 Svaneke Granite

Age: Precambrian
Localities: East Bornholm. The granite is often exposed on the earth surface especially along the coast and few quarries shows deeper parts of the granite bodies. Many shallow boreholes reach the granite.
Rock types: The Svaneke Granite is red grey very coarse-grained granite often strongly weathered especially along the coast.
Thickness: Very thick. The bottom is not known. The boundary to the Bornholm Gneiss is found west of Listed.
Distribution: East Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.3 Vang Granite

Age: Precambrian
Localities: Northwest Bornholm. The granites are often exposed on the earth surface, along the coast and few quarries shows deeper parts of the granite bodies. Few shallow boreholes reach the granites.
Rock types: The Vang Granite is red grey coarse-grained granite with spots of black minerals.
Thickness: Very thick. The bottom is not known. The boundary to the Hammer Granite occurs north of Vang Harbour. The boundary is recognized in the Sjæle Mose quarry at Olsker.
Distribution: Northwest Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.4 Hammer Granite

Age: Precambrian
Localities: North Bornholm. The granite is often exposed on the earth surface, along the coast and few quarries shows deeper parts of the granite bodies. Few shallow boreholes reach the granite.
Rock types: The Hammer Granite is light red grey fine- medium grained granite with characteristic small red hematite dots.
Thickness: Very thick. The bottom is not known. The boundary to the Vang Granite occurs north of Vang Harbour. The boundary can also be seen in Sjæle Mose quarry at Olsker.
Distribution: North Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.5 Alminding Granite

Age: Precambrian
Localities: Central Bornholm. The granite is often exposed on the earth surface and few quarries shows deeper parts of the granite bodies. Very few shallow boreholes reach the granites.
Rock types: The Alminding Granite is light red grey fine to medium-grained granites with characteristic small red hematite dots and often lineation of dark minerals.
Thickness: Very thick. The bottom is not known.
Distribution: Central Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.6 Bornholm Gneiss

Age: Precambrian
Localities: The Bornholm Gneiss is found in the central and northern parts of Bornholm and is know from terrain surface, exposures (quarries) and boreholes.
Rock types: The Bornholm gneiss is a pale grey, grey and brown fine to medium-grained rock with lineation and foliation of light and dark minerals. It is sometimes folded and often cut by fractures.
Thickness: Very thick. The bottom is not known. The boundary to the Svaneke Granite occurs west of Listed.
Distribution: Central and north Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.7 Paradisbakke Migmatite

Age: Precambrian
Localities: The Paradisbakke Migmatite occurs in the eastern part of Bornholm in the Paradisbakke area and north of this area. It is known from the terrain surface, exposures (quarries) and boreholes.
Rock type: The Paradisbakke Migmatite is a migmatitic rock with structures of pale grey granitic and dark grey gneissic veins. It is medium-grained. It is often cut by fractures.
Thickness: Very thick. The bottom is not known.
Distribution: East and north Bornholm.
Literature: Callisen, 1934; Gravesen, 1996, 2006; Micheelsen, 1961.

3.8 Mineralogy and chemistry

The mineralogy and chemistry of the basement rocks have been investigated by several authors who demonstrate that the main mineral composition consist of quartz, feldspars and associated dark minerals as hornblende, pyroxene and mica (Callisen, 1934, 1956, 1957, Micheelsen, 1961, Noe-Nygaard, 1963, Bruun- Pedersen, 1973, Pedersen, 1983, Jensen, 1989). Very few rare minerals occur in the basement rocks and the basement can be described as very low radioactive although some radioactive minerals as gadolinite are found (Sørensen, 1967, Gravesen, 2006). Some ore minerals as galena, titanite, magnetite, chalcopyrite, pyrite, fluorite, jasper and molybdenite together with copper occur local (Bøggild, 1943). The upper part of the basement can be weathered. When it is overlain by the Nexø Sandstone Formation it is weathered to clay minerals and red haematitic material are formed (Bruun-Pedersen, 1973). On other localities the rocks are weathered to kaolinite as the top layers of the Rønne Granite and granite layers below Lower Cretaceous sediments.

3.9 Hydrogeology and hydraulic parameters

The reservoirs in the basement rocks are very restricted; the rocks have no porosity and low fracture permeability. However no hydraulic tests have been done on the basement rocks (in between the large fault bounded valleys) from Bornholm to determine the basic hydraulic characteristics of the rock types.
However, hydrogeological assessments based on pump tests have been carried out on water supply wells situated in the large fault bounded valleys in the Northern Bornholm. Transmissivity in these wells were ranging from 6×10^{-5} to 2×10^{-3} m^2/s and storage coefficient ranged between 4.5×10^{-6} and 3.5×10^{-3} (Miljøcenter Roskilde, 2009a).
Lately has the National Water Resources Model (DK-model) been calibrated in the basement rocks with a horizontal bulk hydraulic conductivity value of 2.6×10^{-7} m/s of the upper approximately 100 m basement with linear valleys in the Precambrian rocks and Quaternary sediments on the top. No flow or a minimum flow is expected to arise in the bottom layer of basement rocks of the model (Troldborg et al., 2006, 2009). The

unsaturated zone is often thick as it is based on fracture permeability where the fracture spacing is high.

The net-precipitation over Bornholm is estimated to 350 mm per year (Troldborg, 2006) and the reservoirs are quickly filled up after rain periods but most of the water is flowing directly into the sea. The groundwater level is often situated a few meters below terrain but in areas with pumping for the drinking water supply the draw down normally lower the groundwater table to large depth (10-30m) for a yield of a few 100 l pr. hour (Gravesen, Bækgaard & Villumsen, 1980).

It is important to emphasize that a limited number of wells are drilled to depths between 100 and 150 m and no wells are deeper than 180 m deep in the basement rocks at Bornholm. The wells are aiming of water supply and shallow geothermal use. The geological description of the lithology in wells is sparse. Borehole geophysical logging ought to be considered of some of these wells. However, no hydraulic knowledge exists in the basement rocks at depths below 100 m at Bornholm.

4. PALEOZOIC SEDIMENTS

The distribution of the Palaeozoic sediments can be seen on map of Bornholm (Fig. 4., VARV, 1977).

4.1 Sandstones and siltstones (Nexø Sst. Formation (NSF), Balka Sst. Formation (BSF), Læsø Formation (LF)).

Age: Early Cambrian
Localities: Quarries on south and east Bornholm, Shallow boreholes.
Lithology: NSF: Red and light red grey medium to coarse-grained sandstone with few silt or mud layers. BSF: Pale grey, grey, black or green grey, hard, fine, medium or coarse-grained sandstone with few silty layers. LF: Black, green or green grey fine-grained siltstone with glauconite and phosphorite nodules and grey medium-grained sandstone.
Thickness: NSF: 110 m, BSF: 80-90 m, LF: 80-100m.
Distribution: South and east Bornholm.
Literature: Grönwall & Milthers, 1916; Gravesen, 1996; Gry, 1936; Hansen, 1936.

4.2 Shale

Age: Early Cambrian, Ordovician, Early Silurian.
Localities: Several small areas on the south coast of Bornholm.
Lithology: Alun Shale (AS): Black shale with a high content of organic matter with thin limestone and clay horizons and large anthraconite concretions. Dicellograptus Shale (DS): Dark grey shale with thin layers of bentonite. Jerrestad Formation and Tommarp Formation (JF+TF): Grey brown shale and clay stone. Rastrites Shale (RS) and Cyrtograptus Shale (CS): Dark grey shale with bentonite and tufaceous sandstone layers.
Thickness: AS: 4.5 m; DS: 12–15 m; JF + TF 9 m; RS: 6–7 m; CS: approx. 220 m.
Distribution: In small fault blocks on the south coast of Bornholm.
Literature: Bjerreskov, 1975; Nielsen, 1995; Poulsen, 1966.

4.3 Komstad Limestone

Age: Ordovician
Localities: Skelbro Limestone quarry and Limensgade, South Bornholm.
Lithology: Black, dark grey or pale grey, hard limestone with grain size from mud to sand.
Thickness: 4–5 m.
Distribution: South Bornholm.
Literature: Gravesen, 1996; Nielsen, 1995; Poulsen, 1966.

4.4 Mineralogy and geochemistry

Hansen (1936), Gry (1936), Bøggild (1943), Bruun-Petersen (1973, 1975) and Marino (1980) have investigated the mineralogy of the sandstones. In the NSF, quartz is the dominating clastic mineral but with 15-20 % feldspar and haematitic cement. A minor content of sphalerite, galena, siderite, pyrite and calcite is present. In the BSF, quartz is by far the most dominating mineral with quartz cement and occasionally glauconite, phosphorite and organic matter. In LF dominates quartz, glauconite and phosphorite in the fine-grained part and quartz with quartz cement and pyrite in the more coarse-grained part.

The shale consists of clay minerals with organic matter, calcite, and traces of jarosite, barite, gypsum, pyrite, sphalerite, and phosphorite. In the bentonite, smectite clay minerals are found (Pedersen, 1989).

The limestone consists almost solely of calcium carbonate with a minor content of clay minerals, sphalerite, pyrite, siderite, phosphorite and gypsum.

4.5 Hydrogeology and hydraulic parameters

The sandstones are important groundwater reservoir based on fractured and crushed layers in different depths in relatively small fault-bounded blocks. The three formations together often form the reservoir (Sørensen & Hansen, 1977, Gravesen et al., 1980).

The horizontal bulk hydraulic conductivity of the sandstones (NSF, BSF, LF) has been estimated to approximately 1.5×10^{-5} m/s. while the siltstones (Green Shales of LF) has a higher bulk value of 1.1×10^{-4} m/s. These three formations form important reservoir on the eastern part of Bornholm.

The bulk hydraulic conductivity of the shales (AS, DS, JF, TF, RS and CS) has been estimated to 6.2×10^{-5} m/s.

Finally, the Komstad Limestone indicates a high permeability in the range of 1×10^{-4} m/s (Troldborg et al, 2006, 2009).

5. MESOZOIC CLAY, SANDSTONE AND LIMESTONE DEPOSITS

The distribution of the Mesozoic deposits is shown on the map of Bornholm (Fig. 4, VARV, 1977). Some of the Jurassic deposits on Bornholm include clay and claystone layers but normally, these occur as thin layers or with very limited distribution and are not included in this report.

5.1 Risebæk Member (Kågerød Formation)

Age: Late Triassic (Late Ladinian – Carnian)
Locality: South coast of Bornholm near Risebæk.
Lithology: Red, green and grey green clay and silt with calcitic or siliceous caliche nodules. The clay alternates with layers of white or greenish sandstone.
Thickness: 60–70 m.
Distribution: South coast of Bornholm.
Literature: Gravesen, Rolle & Surlyk, 1982; Grönwall & Milthers, 1916.

5.2 Hasle Formation

Age: Early Jurassic (Late Sinemurian-Pliensbachian)
Locality: East coast of Bornholm at Hasle and south coast near Korsodde.
Lithology: Yellow brown, fine-grained, firm to hard, limonitic sandstone with thin gravel layers and layers of green grey to brown clay and clay ironstone. Dinosaur footprints and a rich fauna of brachiopods, bivalves, gastropods, belemnites, ammonites, fish and plesiosaur remains are found in Hasle Formation.
Thickness: 80–110 m
Distribution: East and south coast of Bornholm
Literature: Gravesen et al., 1982; Gry, 1969.

5.3 Skyttegård Member (Rabekke Formation)

Age: Early Cretaceous (Early Berriasian)
Localities: South coast of Bornholm near Arnager Bugt, Skyttegård and the Nyker area.
Lithology: Multicoloured sandy to sticky clay: Dark grey, black, green, brown and yellow brown with some silty and sandy intercalations. The content of organic material is very high: plant remains, lignites and rootless. Fine-grained siderite and pyrite are common. A rich fauna of dinosaurs, lizards, crocodiles and primitive mammals is found in the formation.
Thickness: 40- 60 m.
Distribution: South and west coast of Bornholm.

Literature: Gravesen et al., 1982; Gry, 1956, 1969.

5.4 Rødbjerg Member (Jydegård Formation)

Age: Early Cretaceous. (Valanginian)
Localities: Nyker area in Bornholm, Jydegård clay pit.
Lithology: Olive grey, laminated, sticky clay with silt and sand streaks and subordinate thin sandstone, siltstone and clay ironstone beds. Trace fossils, micro flora and some macrofossils are found.
Thickness: 90–110 m.
Distribution: Northeast Bornholm.
Literature: Gravesen et al., 1982; Gry, 1956, 1969.

5.5 Arnager Limestone Formation

Age: Late Cretaceous (Conacian)
Localities: South coast of Bornholm near Arnager.
Lithology: White grey and grey hard chalky limestone with 45–70 % calcium carbonate. The rest consist of clay material and silica spongies and spiculae. A 20 cm thick bottom layer consists of a conglomerate with a hard ground and strongly glauconized and phosphorized gravel and stone particles.
Thickness: Approx. 20 m.
Distribution: Only at the south coast of Bornholm.
Literature: Gravesen, 1996; Ravn, 1918; Tröger & Christensen, 1991.

5.6 Mineralogy and geochemistry

The Mesozoic clays consist mainly of kaolinite and smectite with a minor content of illite (Graff-Petersen & Bondam, 1963). The clays also contain organic material (often a lot), pyrite concretions, limonite concretions and clay ironstone layers. Rørdam (1890) measured the chemical composition. The clay has a content of silica, alumina and iron as the major components.
The Hasle sandstone consists of fine-grained quartz sand with coating of limonite. Quartz and feldspar gravel grains are found in the bottom of erosion troughs.
The fine-grained Arnager Limestone consist of 45-70 % Ca CO_2, silica sponge spiculae and clay minerals. At the bottom of the formation, glauconite and phosphorite occur together with gravels and stones.

5.7 Hydrogeology and hydraulic parameters

The clays of the Risebæk Member and Rødbjerg member have an estimated hydraulic conductivity of 1.4 x 10^{-7} m/s. (Troldborg et al., 2006, 2009). The sand deposits in the

Robbedale and Jydegård Formations intercalated between the clays of the Skyttegård Member and the clays of the Rødbjerg Member are hydraulic connected and is the most important groundwater reservoir (free water table conditions) on Bornholm. The reservoirs are only found in the south-western corner of Bornholm and in the Nyker bloc. The reservoir has a transmissivity of 8 x 10^{-3} m/s and a specific yield of 0.04. Abstraction wells can yield 100 m^3/hr. A yield of this size will only cause a lowering of the water table of 1 m (Gravesen et al, 1980).
The Arnager Limestone Formation has also importance for the drinking water supply. The limestone aquifer has an estimated hydraulic conductivity of approximately 1 x 10^{-4} m/s. Abstraction wells pumping at a capacity of 20–90 m^3/hr lower the water table in the limestone with 1.5–3 m.

6. MESOZOIC AND PALEOGENE CHALK AND LIMESTONE

The distribution of the pre-Quaternary deposits in Denmark can be seen on Fig. 5 (Håkansson & Pedersen, 1992).

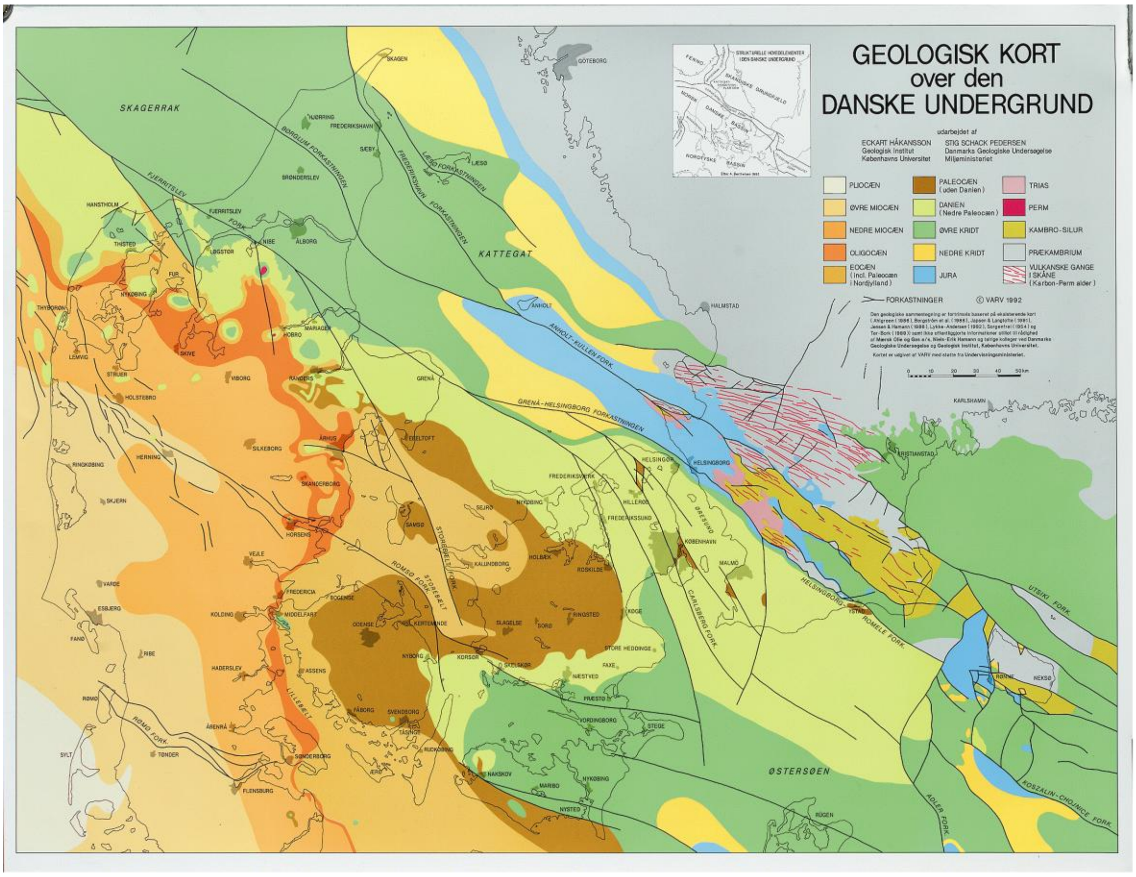


Figure 5. Map of the pre-Quaternary surface: Time units. Original scale: 1:50.000. Legend: Red lines: Precambrian intrusions. Grey: Precambrian. Olive: Cambrian-Silurian: Red: Permian. Light red: Triassic. Blue: Jurassic. Yellow: Lower Cretaceous. Green: Upper Cretaceous. Light green: Danian. Brown: Paleocene. Yellow olive: Eocene. Red brown: Oligocene. Light yellow brown: Lower Miocene. Very light yellow brown: Upper Miocene. White: Pliocene (Håkansson & Pedersen, 1992).

6.1 Tor Formation (Chalk Group)

Age: Late Cretaceous (Late Campanian- Maastrichtian)
Localities: The Danish chalk deposits are known from several coastal cliffs, quarries and boreholes, e.g. Møn and Stevns, Sjælland.

Lithology: Homogenous, fine-grained white or pale chalk with a content of micro and nannofossils. Black flint nodules are found in thin discontinuous bands.
Thickness: 150–250 m.
Distribution: All over the Danish area.
Literature: Surlyk & Håkansson, 1999; Surlyk, Damholt & Bjerager, 2006.

6.2 Sigerslev Member (Tor Formation)

Age: Late Cretaceous (Maastrichtian)
Localities: The Stevns Klint.
Lithology: White chalk matrix with a content of micro fossils deposited on mounds and in horizontal layering, especially in form of bryozoans. The black grey flint nodules show the mound beddings. Burrows and bioturbation are widespread.
Thickness: Approx. 30–70 m.
Distribution: The Stevns Klint area.
Literature: Surlyk et al., 2006.

6.3 Højerup Member (Tor Formation)

Age: Late Cretaceous (Maastrichtian)
Localities: The Stevns Klint area.
Lithology: Pale grey bryozoan wackestone deposited in mounds with layers of flint nodules and a lithified and hard ground top.
Thickness: 2.5–6 m.
Distribution: The Stevns Klint area.
Literature: Surlyk et al., 2006.

6.4 Rødvig Formation

Age: Early Paleocene (Danian)
Localities: The formation occurs mainly in the Stevns Klint.
Lithology: The formation consists of two members with very different lithology: The Fiskeler Member of black clay and the Cerithium Limestone Member of hard, light yellow, strongly bioturbated micrite with black flint nodules.
Thickness: The Fiskeler member is 5–10 cm thick but wedges out from the central part of small basins. Locally 30–45 cm of the limestone is found. The Cerithium Limestone member is mainly 30–70 cm thick but thicknesses up to 150 cm are found.
Distribution: Stevns Klint Sjælland, but correlative layers of the Fiskeler Member are found in other areas of Denmark.
Literature: Surlyk et al., 2006.

6.5 Stevns Klint Formation

Age: Early Paleocene (Danian)
Localities: Stevns Klint and Faxe (Sjælland), Klintholm (Fyn), Sangstrup Klint, Karlby Klint, Bulbjerg, Klim Bjerg and Hanstholm (Jylland). Many shallow boreholes excist over the whole area of distribution. Shallow tunnels and caves are found on Stevns and in northern Jylland at Mønsted and Daugbjerg.
Lithology: A white and light yellow bryozoan wackestone and packstone deposited in asymmetrical mounds and thick layers. The formation includes nodules of flint. Hard grounds occur. The limestone is rich in bryozoans, echinoderms, bivalves and other fossils. In addition, bryozoan rudstone and packstone deposits occur. Locally, these deposits contain octocorals ans serpulids.
Thickness: In the Danish basin, the limestone is max. 175 m thick but it wedges out into lime mudstone deposits in central parts of the basin.
Distribution: The formation is widely distributed in the eastern and northern Denmark (Thomsen, 1995).
Literature: Stenestad, 1976; Surlyk et al., 2006; Thomsen, 1995.

6.6 Faxe Limestone

Age: Early Paleocene (Danian)
Locality: The Faxe Limestone quarry, Sjælland.
Lithology: White and yellow limestone consisting of a network of corals filled with fin-grained matrix muddy lime. The Coral Limestone is often interlayered by bryozoan limestone. The limestone contains a rich fauna corals, molluscs, nautiluses, brachiopods, crustacea and sharks. The limestone can be relatively soft or very cemented and hard.
Thickness: At least up to 30 m.
Distribution: Only in the Faxe area.
Literature: Floris, 1971; Gravesen, 2001; Rosenkrantz, 1937; Thomsen, 1995; Villumsen, 1985.

6.7 Mud Limestone

Age: Early Paleocene (Danian)
Localities: Many shallow boreholes, Mønsted, Daugbjerg (Jylland), northern Sjælland and Copenhagen.
Lithology: White or pale grey, fine-grained muddy limestone with approx. 40 % grain in the silt and sand fractions. The most important components are coccoliths and other nannofossils. Flint nodules are common and can make up to 30 % of the volume.
Thickness: More than 100 m.
Distribution: Northern Jylland and northern Sjælland.
Literature: Stenestad, 1976; Thomsen, 1995.

6.8 København Limestone Formation

Age: Early Paleocene (Danian)
Localities: Copenhagen Area, Northern Sjælland, shallow boreholes
Lithology: Calcarenitic cemented hard limestone with 20–30 % limestone fragments in sand grain-size and the rest as fine-grained sand and clay. The limestone is faintly layered and hard grounds occur. The limestone has a large content of flint (chert) in continuous, often relatively thick layers. The limestone is bioturbated in some of the layers and the burrows are often filled by flint.
The limestone is cut by fractures and the surface layers below the Quaternary deposits are often crushed because of eroding glaciers during the ice ages (called "Knoldekalk"). The limestone is cut by the Carlsberg fault, the faults of the Søndersø graben, the faults of the Alnarp graben and the faults of the Roskilde faults complex.
Thickness: Approx. 40 m in the Copenhagen area and Sjælland.
Distribution: Northern Sjælland, northern Hornsherred and northern Odsherred, Copenhagen area, southern Øresund.
Literature: Gravesen & Pedersen, 2006; Nielsen, 1976; Stenestad, 1976.

6.9 Lellinge Greensand

Age: Late Paleocene (Selandian)
Localities: Lellinge stream, Copenhagen area, many shallow boreholes. East Jylland.
Lithology: A basal conglomerate is known from the Copenhagen area, Lellinge and a few localities in Jylland. The main lithologies are intercalated green and olive grey, glauconitic greensand, green sandstone, clayey or marly greensand and greensand limestone. Black sticky clay is also a part of the sequence. It has been suggested that the unit seems to interfinger with the Kerteminde Marl, which also overlie the Lellinge Greensand. However, borehole-logging investigations show that the formation is mainly overlain by the Kerteminde Marl.
Thickness: The thickness is 5–10 m in the easternmost part of Sjælland. In the central part of Sjælland shallow boreholes show that the unit is at least 30 m but could be up to 50–60 m from the Ringsted and Sorø areas towards the southeast (Gry, 1935). Nevertheless, the distinction in the boreholes between the clays of the formation and the Kerteminde Marl is not always clear. Towards the west and northwest, the unit becomes thinner. In Northern Jylland, the unit is thin.
Distribution: Sjælland and northern Jylland but absent on Fyn and large parts of Jylland.
Literature: Clausen & Huuse, 2002; Gry, 1935; Hansen, 1971; Klitten, 2003; Schnetler, 2001.

6.10 Mineralogy and chemistry

Chalk is a pelagic micritic limestone predominantly composed of skeletal debris from calcareous nannofossils, mainly coccoliths. The Chalk is very fine-grained with particle

size less than 100 µm, but the majority is less than 5 µm (Hancock, 1975). The carbonate fraction is dominated by thermo-dynamically stable low-magnesium calcite ($CaCO_3$), and the non-carbonate components are dominated by clay minerals (primarily montmorillonite and illite) and flint together with some clay-graded quartz, glauconite, phosphate and sulphides, mainly as pyrite (Håkansson et al., 1974; Hancock, 1975; Morgan-Jones, 1977). The non-carbonate fraction often makes up only a few percent, and normally less than 10 % of the Chalk. In the thin marl, seams and flint bands in the non-carbonate fraction can be higher. The Chalk is often regarded as very homogenous, but detailed studies of the North Sea Chalk gave revealed cyclicity with alternating calcite and clay contents in the deposits (Stage, 2001).
Cretaceous and Danian Chalk and limestone: Calcite, $CaCO_3$, is the total dominating mineral while the chert/flint layers consist of SiO_2. Other minerals are pyrite and clay minerals. The Fiskeler unit consists of $CaCO_3$ and clay minerals and the rare metal iridium is also found.
Selandian greensand deposits: The greensand deposits consist of lime sand. Calcareous cement, glauconite, quartz and pyrite are found in the limestone.

6.11 Hydrogeology and hydraulic parameters

The Chalk Group sediments form an extensive and thick deposit in the Danish area, extending into the North Sea and the Baltic, and can be found regionally from Ireland to the Black sea and southern France. Chalk is a unique dual-porosity reservoir rock with a high-porosity matrix, which is relatively impermeable. On the other hand, fractures that dominates the flow mechanisms in many chalk systems (by offering preferential flow paths for fluids) occurs as well. The upper parts of the formation in eastern Sjælland have largely resisted recrystallization and lithification. Therefore, a high primary porosity of 30–50 % is preserved (Frykman, 2001). However, owing to the small grain size, the permeability is generally low (Price et al, 1993).
Frykman (2001) has investigated the spatial distribution of porosity and permeability in the Tor Formation and Danian age chalks in detail. The investigation was based on a comparative study of petro physical data and an analogue study in Sigerslev quarry. Permeability and porosity in the white chalk (Sigerslev Formation) has been measured to 45–50 % and less than 10 mD (or < 10^{-8} m/s), respectively. The thin Rødvig Formation has 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 between 35 and 45 % and a large range of permeability, between 80 and 500 mD. Another study in Sigerslev quarry has focused on mapping and characterization of fracture networks in the same chalk formations as Frykman (2001) and attempted to identify the larger-scale preferential flow paths using heat as tracer (Rosenbom and Jakobsen, 2005).

The transmissivity of the chalk aquifers has been observed to decrease with depth. This is often attributed to a decline in fracture density and a reduction in aperture of primarily the bedding-plane-fractures. Therefore, an effective aquifer might exist only in the parts of the chalk that are close to the ground surface (Downing and Headworth, 1990; Price et al., 1993; Williams et al., 2006). The sedimentary basin in Sjælland has been subdivided into three hydrogeological sections: (i) a shallow freshwater section; (ii) an underlying saline section with a near hydrostatic pressure distribution; and (iii) a deep saline "geopressured" zone (Bonnesen et al., 2009).

The conditions in the Lellinge Greensand are dominated by the clayey limestone and clay deposits. The secondary fracture permeability is the basis for an abstraction of groundwater in the central part of Sjælland (Kelstrup, Binzer & Knudsen, 1981).
The pumping tests show that transmissivities are in the order of 10^{-2} m^2/s and storage coefficients in the order of 10^{-4} (Kelstrup & Binzer, 1982).

7. PALEOGENE CLAY DEPOSITS

The distribution of the deposits can be seen in Fig. 5.

7.1 Kerteminde Marl

Age: Late Paleocene (Selandian)
Localities: Lundgård Klint and Klintholm (Fyn), Jernhatten and Svejstrup (Jylland). Many shallow boreholes exist.
Lithology: Pale grey silty marl and calcareous marine clay often with siliceous layers, strongly bioturbated and often strongly pyritic. The bottom layer of the unit is conglomeratic and it contains glauconite. The top layers include non-calcareous, pyritic, glauconitic clay and non-calcareous glauconitic greensand. The Kerteminde Marl probably overlies the Lellinge Greensand deposits in large parts of Sjælland (see above). In Jylland and Fyn, the unit rest directly on Danian limestone (Svejstrup, Klintholm).
Thickness: From 12 to approx. 136 m but thickest in central and western Sjælland.
Distribution: Widely distributed below the Quaternary deposits in Sjælland, Fyn and eastern Jylland.
Literature: Gry, 1935; Heilmann-Clausen, 1995; Klitten, 2003; Thomsen & Heilmann-Clausen, 1985.

7.2 Æbelø Formation

Age: Late Paleocene (Selandian)
Localities: Æbelø (Northwest Fyn), Rugaard (Djursland, Jylland).
Lithology: Non-calcareous and slightly calcareous sticky-silty grey marine clay, sometimes black. Slightly siliceous layers occur.
Thickness: 16–57 m.
Distribution: Found in the completely Danish area.
Literature: Bøggild, 1918; Heilmann-Clausen, 1985, 1995.

7.3 Holmehus Formation

Age: Late Paleocene (Selandian-Thanetian)
Localities: Ølst, Odder (Jylland), Holmehus, Røjle (Fyn).
Lithology: Green, blue, dark red and red brown very fine-grained sticky (plastic) non-calcareous marine clay with indistinct bedding. Burrows and lenticular sideritic and phosphatic concretions occur in the clays (Fig. 6).
Thickness: 5–15 m at Viborg, 3–4 m at Ølst, approx. 40 m at Odder and 40 m at Rødby.
Distribution: Widely distributed in the Danish Subbasin.

Literature: Dinesen et al., 1977, Heilmann-Clausen, 1985, 1995, Heilmann-Clausen et al., 1984.

7.4 Østerrende Clay

Age: Late Paleocene (Thanetian)
Localities: Boreholes in the Storebælt.
Lithology: Grey non-calcareous silty marine clay.
Thickness: Approx. 6 m
Distribution: Very limited in central Denmark.
Literature: Heilmann-Clausen, 1985, 1995.

Figure 6. Excavated profile in fine-grained clay from the Holmehus/Ølst Formation (From Gravesen & Pedersen, 2009).

7.5 Stolleklint Clay

Age: Early Eocene (Ypresian)
Localities: Stolleklint, Svaleklint, Ølst, Hinge (Jylland).

Lithology: Dark grey, non-calcareous, laminated marine clay, rich in organic matter occasionally shaly with silicifereous horizons and burrows. A few layers of volcanic ash occur.
Thickness: Approx. 15 m
Distribution: During the Danish Subbasin
Literature: Heilmann-Clausen et al., 1984; Heilmann-Clausen, 1995.

7.6 Ølst Formation

Age: Early Eocene (Ypresian).
Localities: Ølst, Hinge (Jylland), Albæk Hoved, Ørby, Holmehus (Fyn).
Lithology: Dark grey or olive black, silty and sandy, non-calcareous marine clay, intercalated with black and dark grey volcanic ash layers (up to 20 cm thick). The clay is laminated or structureless. Some layers are siliciferous and calcium carbonate cemented layers (cementsten) occur as well (Subdivided into two members).
Thickness: 9–15 m.
Distribution: The Danish Subbasin excluding the Mors and Fur areas.
Literature: Andersen, 1937; Heilmann-Clausen, 1984.

7.7 Fur Formation

Age: Early Eocene (Ypresian).
Localities: Western Limfjord, Fur, Mors (Jylland).
Lithology: Light, white or black, laminated, slightly clayey marine diatomite (moler) intercalated with basaltic and acid volcanic ash layers (170 layers). Siliciferous layers and calcium carbonate cemented layers (cementsten) occur. Many fossils: Birds, insects, fishs and plants are found and some layers are strongly bioturbated. (Subdivided into two members).
Thickness: Approx. 60 m.
Distribution: Northwestern Jylland.
Literature: Andersen, 1937; Bøggild, 1918; Pedersen, 1981; Pedersen & Surlyk, 1983.

7.8 Røsnæs Clay Formation

Age: Early Eocene (Ypresian)
Localities: Røsnæs (Sjælland), Albæk Hoved, Fur, Mors, Ølst, Odder (Jylland).
Lithology: Mainly red, red brown and yellow brown, calcareous, very fine-grained, sticky, plastic marine clay with microfossils and some trace fossils. (The formation is subdivided into six units with green and dark grey colours). Green volcanic ash layers are found throughout the formation.
Thickness: 3–28 m.
Distribution: Large part of the Danish Subbasin.
Literature: Andersen, 1937; Heilmann-Clausen et al., 1985.

7.9 Lillebælt Clay Formation

Age: Early - Middle Eocene (Ypresian-Lutetian)
Localities: Along Lillebælt between Fredericia and Trelde Næs, Hinge, Albæk Hoved (Jylland), east of Røgle Klint (Fyn).
Lithology: Green, red brown and grey green, non-calcareous, very fine-grained, sticky plastic marine clay at the bottom and dark green to grey, slightly calcareous plastic clay at the top. Trace fossils occur occasionally and very thin layers rich in organic matter and thin volcanic ash layers are found in the lower part. Concretions of different compositions occur. A rich fauna of crinoids, molluscs, crabs, asterias, fish and sharks. (The formation is divided into six units).
Thickness: 40–100 m.
Distribution: Most of the Danish Subbasin.
Literature: Dinesen et al., 1977; Heilmann-Clausen et al., 1985.

7.10 Søvind Marl Formation

Age: Middle–Late Eocene (Lutetian-Bartonian-Priabonian)
Localities: Søvind, Trelde Næs, Nørre Vissing (Jylland).
Lithology: Pale grey to light olive grey or white, very fine-grained, sticky marine marl with a high content of $CaCO_3$ (often 20–50 %, but up to 70 %). Thin layers with lower content of $CaCO_3$ occur. The marl is strongly bioturbated without layering. Few carbonate and barite concretions occur.
Thickness: 4–90 m.
Distribution: In the Danish Subbasin but absent in the western Limfjord area.
Literature: Dinesen et al., 1977; Heilmann-Clausen, 1985.

7.11 Viborg Formation

Age: Early Oligocene (Rupelian)
Localities: Ølst, Hinge, Sofienlund, Branden, Grundfør (Jylland). Boreholes: Viborg-1, Linde-1.
Lithology: A bottom layer of grey green glauconitic calcareous sticky marine clay (Grundfør Member) is overlain by grey sticky marine clay and silt and silty grey brown, non-calcareous organic rich clay.
Thickness: 58–85 m
Distribution: In the Danish Subbasin between Salling, Mariager Fjord and Horsens Fjord (Jylland).
Literature: Christensen & Ulleberg, 1973, 1974, 1987; Heilmann-Clausen, 1985.

7.12 Linde Clay

Age: Early Oligocene (Rupelian)

Localities: Borehole: Linde-1.
Lithology: Grey brown sticky and silty marine clay, which is glauconitic in the bottom layer.
Thickness: Approx. 20 m.
Distribution: Very limited.
Literature: Heilmann-Clausen, 1995.

7.13 Hvorslev Clay

Age: Early Oligocene (Rupelian)
Localities: Branden and Hvorslev. Boreholes: Viborg-1, Linde-1, Harre borehole.
Lithology: Green strongly glauconitic sandy clay, clayey sand and sandstone.
Thickness: 4–8 m.
Distribution: Northern part of Jylland, south of Limfjorden, between Salling and Hvorslev.
Literature: Ulleberg, 1987.

7.14 Branden Clay/Skive Clay

Age: Late Oligocene (Chattian)
Localities: Branden, Hesselbjerg, Cilleborg, Skive. Boreholes: Linde-1, Viborg-1, Harre, (Jylland).
Lithology: Grey green silty to sticky non-calcareous or calcareous clay with glauconite, mica and pyrite. Large calcareous fractured concretions (Septarian) occur.
Thickness: 45–88 m.
Distribution: South of Limfjorden from Struer, Salling, Hobro, Viborg to Mariager (Jylland).
Literature: Ulleberg, 1987.

7.15 Haverslev Greensand

Age: Late Oligocene
Localities: Only known from shallow borehole in an area around Haverslev north of Mariager Fjord and a local occurrence at Lyby Klint (Jylland).
Lithology: Green grey strongly glauconitic sand, sand stone or siltstone. The unit can possibly be correlated with the bottom layer of the Brejning Clay.
Thickness: 2–20 m.
Distribution: Haverslev area.
Literature: Fredericia, 1989.

7.16 Mineralogy and chemistry

The Kerteminde Marl is dominated by a high smectite content and absence of kaolinite (Tank, 1963).
Holmehus Formation contains mainly smectite.
The clay content of the diatomites of the Fur Formation have been analysed for mineralogy and chemical composition (Pedersen et al., 2004). The dominant clay mineral is smectite, but several subordinate minerals occur. The clay content is 30–45 % and the bulk chemical analyses show dominance of silica, aluminium and iron.

The Upper Paleocene and Eocene clay deposits mainly consist of smectite and minor amounts of illite and kaolinite, but in some of the layers, the amounts of the three clay minerals are equal. The manganese and iron content generally varies with the colour variation of the clays. Organic matter and pyrite occur in some of the horizons (Heilmann-Clausen et al., 1984). Calcium carbonate and phosphorite concretions, fine-grained calcium carbonate, glauconite and silica horizons vary throughout the formations.

7.17 Hydrogeology and hydraulic parameters

The hydrogeological and hydraulic characteristics of Paleogene clays in Denmark will be treated geographically in this section. Late Paleocene clay and marl deposits occur in the central and western part of Sjælland and in the Lolland/Falster area. Eocene and Oligocene clay deposits are located in East and Northern Jutland.

Central and West Sjælland: The less permeable Kerteminde Marl (Late Paleocene) overlies the more permeable Lellinge Greensand deposits in large parts of Sjælland. However, the spatial distribution and thickness of especially the marl deposits are inadequate described due to lack of boreholes penetrating the Kerteminde Marl and Lellinge Greensand. Moreover, there are significant lacks of indirect geo-information from geophysical surveys in especially the western part of Sjælland. Around Ringsted, the thickness of the Kerteminde Marl is about 135 m and smaller thicknesses are expected westward. At central Sjælland, the greensand deposits are an important groundwater reservoir but the deposits disappear in westward direction and it is certain that the greensand do not exist in western part of Sjælland. Detailed geological information is obtained along the east bridge of Storebælt and the pre-Quaternary deposits consist of more than 40 m of Kerteminde Marl resting on the Danien limestone. The Lellinge Greensand has not been observed along that east bridge of Storebælt (Larsen et al, 1982).

Hydraulic characteristics of the Kerteminde Marl have only been very sparsely quantified. Permeability determined on few cores from a single well drilled in the Suså region together with knowledge from the Storebælt (pump tests) and Nyborg area (groundwater modelling) has been summarised by Møller & Richard (2006). The horizontal hydraulic conductivity range between 1 x 10^{-7} to 1x10^{-5} m/s and the vertical hydraulic conductivity are ranging from 1.6 x 10^{-8} to 2.8 x 10^{-7} m/s. Matrix permeability ranges between 1 x 10^{-11} to 1 x 10^{-10} m/s. The drinking water interests at central Sjælland are significant. The latest overview on the groundwater capture zones around the Water Works at central and western Sjælland indicate that only coastal near areas can be suggested as potential disposal sites in this region of Denmark (Miljøcenter Roskilde, 2009b).

Lolland-Falster: At the southern part of Lolland, three different low permeable clay materials are deposited on top of each other: Æbelø Formation, Holmehus Formation and clayey till.
West of Rødby, the top of the fine-grained clay is situated 40–50 m below terrain. The lower boundary is unknown west of Rødby, but one well indicates the lower surface to be at 90 m depth.
Around Rødbyhavn, fine-grained clay is found at 12–36 m below terrain. Just north of Rødby no pre-Quaternary clay is situated at all.
Miljøcenter Nykøbing reports limited groundwater interests for the southern part of Lolland. However, several water supply wells aiming for household in shallow sandy aquifers embedded in a very hard carbonate enriched clayey till (similar to "Københavnermorænen" or Murstens-moræne) occur locally, above the plastic clay.
Thus, some drinking water interests likely need to be considered in the local extended shallow aquifers.

At the very southern part of Falster, south of Gedesby Nyby, the top of the plastic clay is situated from about 15 to 18 m below terrain and the bottom of the plastic clay is found at depths between 85 and 106 m. No hydraulic information is available but the area is considered to hold limited drinking water interests.

South coast of Fyn and islands south of Fyn: Plastic clay deposits from the Holmehus and Æbelø Formations occur at southern Langeland and along the south and west margin of Fyn. The clay is widely distributed on the southern Langeland, south of Rudkøbing. At Fyn, the clay is not investigated but is often tectonised to such a degree that the situation is a disturbed hydrogeological setting. Saltwater intrusion also needs to be considered on the islands south of Fyn. Hydraulic characteristics of the plastic clay in this area have not been investigated.

East and central Jylland: The interesting Paleogene clay deposits are found in the following areas: 1. East Jylland (Fredericia-Vejle): Oligocene clays/Søvind Formation, 2. Central Jylland (Ølst): Ølst, Røsnæs and Lillebælt Formations, 3. Central Jylland (Viborg): Viborg Formation/Branden Formation. Hydraulic information about these clay deposits is very limited as the clays normally are regarded as the lower boundary for the groundwater reservoirs. Therefore very few indications concerning transport through the clays occur. Deep-seated groundwater is known from oil and gas exploration. The groundwater often has a very high content of sodium chloride, probably originating from the Permian salt deposits and the pressure on the groundwater is very

high. Transport in the fine-grained Paleogene clays will probably be vertical upwards from the deep groundwater and this will cause a higher sodium chloride content in the shallow groundwater. Examples of this are very few and knowledge of the groundwater transport in the clays is very limited.
The Paleogene clay deposits are often glaciotectonic disturbed and are included in very restricted reservoirs.

Northwestern Jylland (Mors/Fur): The Fur formation mainly consists of diatomites (moler). All known deposits are strongly disturbed by glaciotectonics and form hills in the surface and isolated sheets in the subsurface. The deposits can deliver a restricted amount of groundwater for local house holding.

8. NEOGENE CLAY AND SILT DEPOSITS

See Fig. 5 for the distribution of the deposits

8.1 Brejning Clay Member (Vejle Fjord Formation)

Age: Late Oligocene–Early Miocene (Chattian–Aquitanian)
Localities: East Jylland, in coastal cliffs at Brejning, Lillebælt area, Vejle Fjord and Horsens Fjord. In boreholes: Viborg-1, Harre (Jylland), Middelfart (Fyn).
Lithology: Green and yellow brown, sandy clay with glauconite and intercalations of glauconite sand, often iron cemented (Øxenrade sandsten). This clay is superimposed by yellow brown bioturbated, silty clay with a high content of organic matter and some lenses of fine sand.
Thickness: 4m – ?
Distribution: In the Danish Subbasin from Mors, Salling, Mariager along the east coast of Jylland to the Lillebælt area.
Literature: Larsen & Dinesen, 1959; Larsen, 2002; Rasmussen, 1995; Ulleberg, 1987; Dybkjær & Piasecki, 2010.

8.2 Vejle Fjord Clay Member (Vejle Fjord Formation)

Age: Early Miocene (Aquitanian)
Localities: East Jylland, in coastal cliffs at Brejning and Lillebælt area. In boreholes: Viborg-1, Harre.
Lithology: Yellow-brown, bioturbated silty clay with a high content of organic matter and white sand lenses and layers. Thin interlayered sand and mud deposits are common.
Thickness: 5.5 m – ?
Distribution: East Jylland from Limfjorden to Lillebælt.
Literature: Larsen & Dinesen, 1959; Rasmussen, 1995, 2004.

8.3 Klintinghoved Formation

Age: Early Miocene (Aquitanian–Burdigalian)
Localities: Few shallow boreholes.
Lithology: Black and brown micaceous, weakly calcareous, silty clay with glauconite and layers of fine-grained mica sand.
Thickness: 35 m?
Distribution: Southern Jylland.
Literature: Rasmussen, 1961; Sorgenfrei, 1958, Dybkjær & Piasecki, 2010.

8.4 Arnum Formation

Age: Early–Middle Miocene (Burdigalian–Langhian)
Localities: Many shallow boreholes.
Lithology: Alternating thin layers of micaceous silt, clay and fine-grained sand with concretions, many fossils and layers with concentrations of fossils.
Thickness: Approx. 60–70 m.
Distribution: Central Jylland.
Literature: Rasmussen, 1961; Rasmussen, 2004; Sorgenfrei, 1958.

8.5 Hodde Formation

Age: Middle Miocene (Langhian–Serravalian)
Localities: Alsigkær, Lille Spåbæk (Jylland), shallow boreholes.
Lithology: Black and black brown fat, silty clay with green ellipsoidal or irregular shaped pellets, glauconite and a high content of organic matter. Occasionally, the clay is laminated and burrows occur in some horizons. A bottom layer (30–50 cm) consists of quartz sand and gravel (Hodde sand).
Thickness: 4–7 m.
Distribution: The central and southwestern part of Jylland.
Literature: Dinesen, 1976; Larsen & Kronborg, 1994; Nielsen, 1984; Rasmussen, 1961, 1966.

8.6 Ørnhøj Formation

Age: Middle Miocene (Late Serravalian)
Localities: Southern and western Jylland: Ørnhøj, Bording, Give. Shallow boreholes.
Lithology: Green and brown clay with high concentrations of fine-grained sand sized green glaukonit pellets. In the upper part, goethification of glaukonit is common.
Thickness: 2–4 m.
Distribution: Southern and western Jylland.
Literature: Dybkjær & Piasecki, 2010; Rasmussen et al. In prep.

8.7 Gram Formation

Age: Late Miocene (Tortonian)
Localities: Gram Brickworks, Esbjerg, Måde, many shallow boreholes (Jylland).
Lithology: Brown and yellow brown silty or sticky mica clay with concretions and ellipsoidal brown, black and green pellets. Burrows filled with pyrite occur in the upper part. Several fossils: Molluscs, whales, sharks.
Thickness: 23–31 m (overlaid by approx. 5 m Gram silt and sand).

Distribution: The central and southwestern part of Jylland.
Literature: Dinesen, 1976; Rasmussen 1961, 1966; Rasmussen & Larsen, 1989; Dybkjær & Piasecki, 2010; Rasmussen et al. In prep.

8.8 Mineralogy and chemistry

Investigation of the mineralogy of the Vejle Fjord Formation is carried out by Larsen & Dinesen (1959) and Rasmussen (1993). In both investigations, the coarse fractions and the clay fraction were dominated by quartz and kaolinite.
The mineralogy of the Hodde Formation (analysed by Nielsen, 1984) shows the clay minerals illite, kaolinite and smectite.
The mineralogy and chemistry of the Gram Formation is described by Dinesen (1976) and Rasmussen & Larsen (1989). The formation contains glauconite, pyrite, Fe-poor and Fe-rich concretions, clay ironstone concretions, kaolinite, illite and smectite.

8.9 Hydrogeology and hydraulic parameters.

Neogene marine clay and silt deposits are located in the Western Jutland in an area from Holstebro in the north to Varde/Grindsted in the south and from the eastern side of Ringkøbing Fjord to a line through Karup-Ikast-Brande. The distribution of sand-rich and clay/silt-rich deposits within that area has been outlined in a palaeogeographical model developed by Rasmussen (2004). The Arnum, Hodde, Ørnhøj and Gram Formations (Early to Late Miocene) represent a clay-rich sedimentation of 90–110 m in total. In accordance to Rasmussen (2004), it is very likely that the Odderup Formation and Bastrup Sand (both sand deposits) are intercalated in the Hodde/Gram Formations and the Arnum Formation. If this is the case, then the hydrogeological situation change from an approximately 100 m continuous vertical sequence of clay and silt deposits to a 60–70 m thick clay sequence separated from the clay-rich Arnum Formation by an unknown thickness of sand deposits from the Odderup Formation and Bastrup Sand. The three low permeable Neogene formations are underlain by an at least 100 m thick sandy aquifer (Ribe Formation (Late Oligocene - Early Miocene)). The Ribe Formation aquifer(s) contains several unexplored aquifers, which are receiving increasing interest. The Ribe Formation aquifers are assessed to be vulnerable and very important for the present and future water supply in the central and western Denmark (Rasmussen and Dybkjær, 1998; Rasmussen et al., 2007; Scharling et al., 2009). The hydraulic characteristics of the low permeable sediments Arnum, Hodde and Gram Formations are poorly known.
Buried valleys in Jylland have to be taken into account in most places of Jylland. The buried valleys are often cross cutting the surrounding pre-Quaternary sequence of Tertiary clay and sandy/silty deposits. Geophysical investigations have been carried out thoroughly in large parts of Jylland to map the extension of the valleys (Sandersen & Jørgensen, 2003, Jørgensen and Sandersen, 2006). Significant water supply interests are connected to these geological structures in the subsurface. Hydraulic effects of the

buried valleys on the Miocene layered groundwater aquifer system have been evaluated by Seifert et al. (2008), where a significant impact was found on the groundwater vulnerability. It may be very likely that the buried valleys also affect the hydraulics of the adjacent low-permeable clay deposits. Any potential location of a radioactive repository has to be considered in a hydrogeological context without any impact from these buried valleys.

9. QUATERNARY CLAY DEPOSITS

The distribution of the Quaternary deposits on the terrain surface is shown in Fig. 7 (Pedersen, 1989). The Quaternary sediments cover all the pre-Quaternary deposits except on e.g. Bornholm and in several quarries and pits.

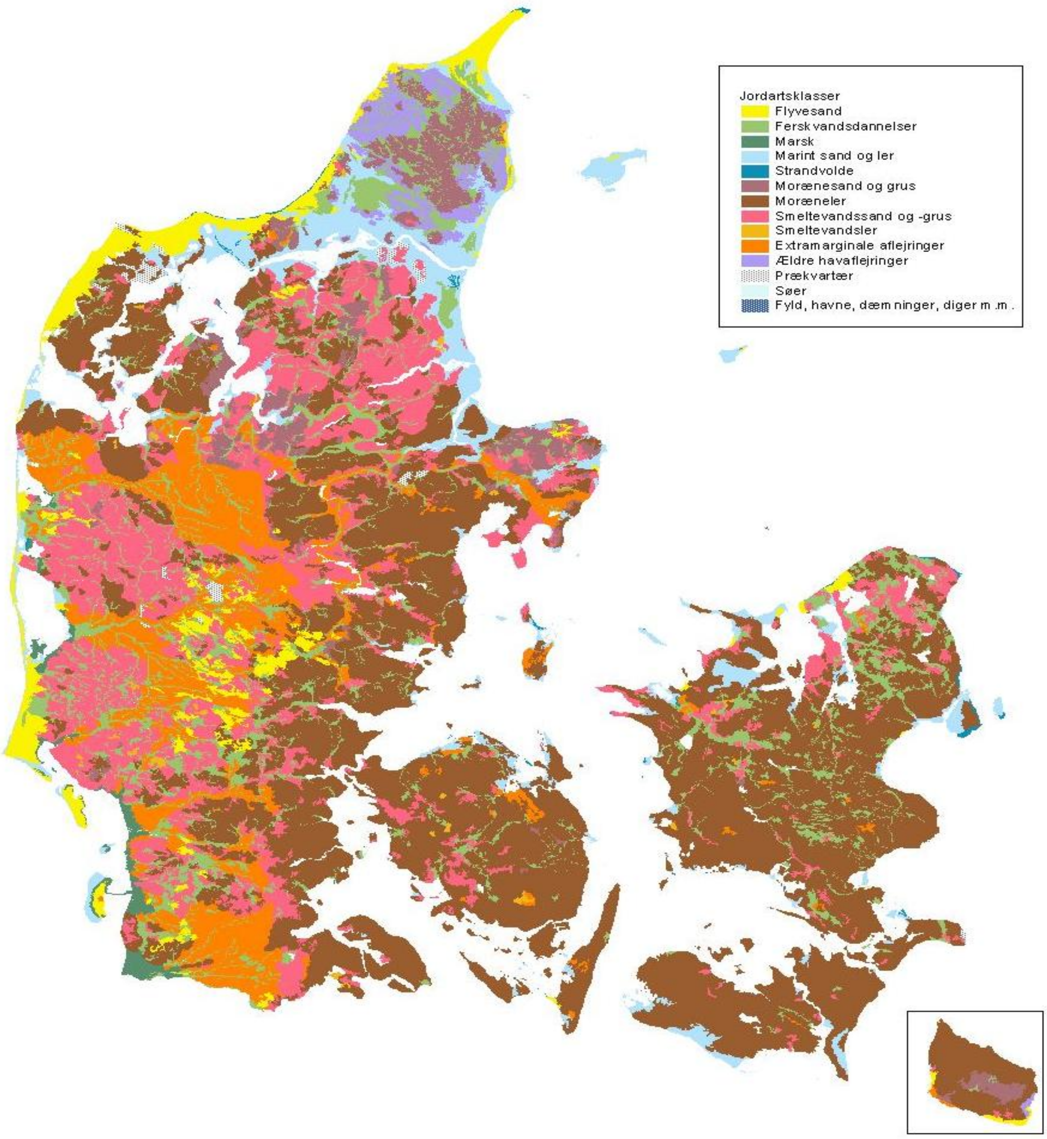


Figure 7. Map of the Quaternary surface deposits. Original scale: 1:200.000.
Legend: Brown: clayey till. Light brown: sandy till. Red: meltwater sand and gravel. Orange: sandur sand and gravel. Purple: Late glacial marine deposits. Light blue: Holocene marine deposits. Green: Holocene freshwater deposits. Yellow: aeolian sand (From Pedersen, 1989).

9.1 Clayey till deposits

Age: Pleistocene (several glacials).

Lithology: More than 40 % of the Danish grund surface is covered by clay till. The Danish clay till is a heterogeneous mixed sediment containing at least 12–14 % material in the clay fraction. The rest of the sediment consists of sand, gravel and stone. In the clayey till body, sand and silt lenses occur. In addition, layers (floes) of limestone, chalk or other pre-Quaternary sediments are seen in areas, where these sediments are found in the subsurface. The tills are deposited by a glacier either from below (lodgement till), inside the glacier after melting (ablation till) or from the top by sliding (flow till). Depositional or tectonic structures often occur in the till deposits as faults or folds. Caused by freeze-thaw processes, bioturbation or glaciotectonic pressure clay till deposits are often cut by macro pores and fractures, that can act as pathways for water and chemicals from the earth surface to the groundwater.

Thickness and distribution: Many clay units have a large horizontal distribution and can be rather thick as well. Owing to at least four glaciations (Menapian, Elsterian, Saalian, Weichselian) during the Pleistocene and several advances and retreats of the glaciers during each glacial, many separate clay till layers can be traced and the total layer package is rather thick. Meltwater sand and gravel deposits are often found between the till layers.
The permeability of the clayey tills is based on a mixture of primary permeability caused by small pores (micro pores) in the till and secondary permeability caused by the macopores that can be traced down to approx. 10 m below the earth surface. Recently, it was proven that the vertical and horizontal macro pores are the most important factors concerning the hydraulic conditions (Fig. 8).

Literature: Houmark-Nielsen, 1987; Klint, 2001; Klint & Gravesen, 1999.

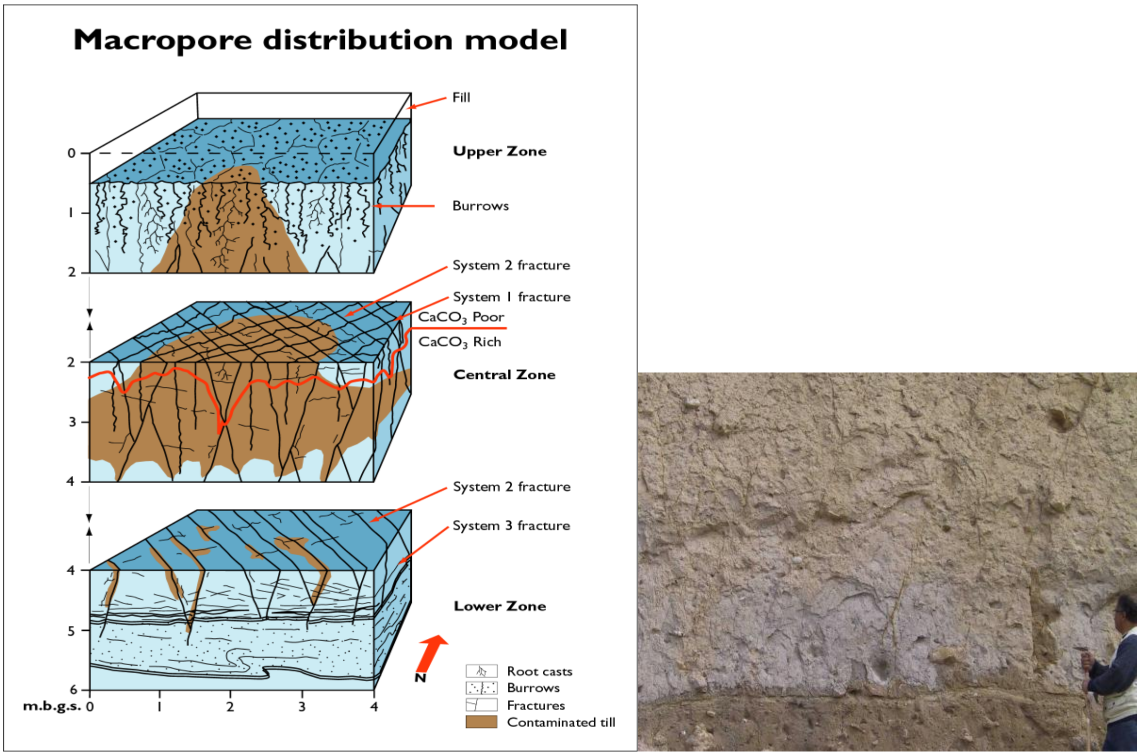


Figure 8. 3-D geological model of the upper 6 m clayey till at Flakkebjerg, Sjælland (left). Photo showing fractures in clayey till (right). (After Klint & Gravesen, 1999).

9.2 Meltwater clay deposits

<u>*Age*</u>: Pleistocene (several glacials and late glacials).

<u>*Lithology*</u>: Meltwater clay is deposited in meltwater from the glaciers, often in ice lakes formed by the terrain and the glacier front, during the glacials or the late glacials. The dominant grain sizes are in the clay and silt fractions but sand and gravel may occur. The clay is often called stone less clay. The larger fraction such as stones is deposited from floating ice flakes or icebergs into the lakes. Normally, the clay is structureless but structures formed by down slid material and water escapes are found. A rhythmic layering as varv has also been formed in many lakes (Hansen, 1940). Glaciotectonic pressures and extential faulting have caused fractures and faults in the clay deposits.

<u>*Thickness and distribution*</u>: The thickness and distribution of the lake deposits are normally limited although large, thick clay bodies from the Saalian and Weichselian glacials have been known near the terrain surface. However, in many areas, the clay has been dug for use in brickworks. Examples of large ice lakes are the Egernsund ice lake system in southern Jylland and the Steenstrup ice lake on Fyn (Hansen, 1940). Meltwater clay deposits from Late Elsterian of great thickness (from approx. 7 m at the Venø Bugt area to between 50 m and 100 m towards the east) and large horizontal

distribution occur in Jylland south of the Limfjord as documented from many boreholes (Jensen, 1985, Gravesen, 1993).
Large amounts of Weichselian meltwater clay are also deposited in North Jylland.
The permeability of the clay deposits is related to small silt and sand lenses and macro pores but otherwise poorly known.
Literature: Gravesen, 1993; Hansen, 1940; Jensen, 1985.

9.3 Interglacial marine clay deposits

Age: Pleistocene (Cromerian, Late Elsterian-Holsteinian, Eemian).

Lithology: The marine deposits from the Cromerian interglacial are poorly known. From the Holsteinian and Eemian, relatively thick sequences of marine clay deposits are known at many sites in Denmark.
The Late Elsterian-Holsteinian marine clays are silty, olive gray, often with a lot of organic matter and shells. These clays are found in southwestern Jylland south of Varde where the deposits can reach a thickness of 130 m. (Knudsen & Penney, 1987, Gravesen et al., 2004). In addition, the Late Elsterian-Holsteinian clay is recognised in northern Jylland and in the Limfjord area, but here the thickness is more limited (Jensen & Knudsen, 1984). Other areas are Vejen-Kolding, south Djursland and northwest and central Sjælland. The deposits are often glaciotectonic disturbed and it can be difficult to identify in-situ sediments.
The Eemian clay deposits consist of olive green, silty marine clay often with shells. The deposits are found along the west coast of Jylland, south-eastern Jylland, northern Jylland, southern Fyn and north-eastern Sjælland. The marine Eemian deposits are between a few meters and up to 40–50 m thick. It is known from several coast cliffs and boreholes that the deposits are often glaciotectonic disturbed.
In the north-eastern part of Jylland, marine Saalian, Eemian and Weichselian clay deposits (The Skærumhede Series) occur in 120-160 m thick sequences, deposited continuous during the time span. In some parts of the area, the deposits are glaciotectonic disturbed.
The hydraulic parameters of the clays are not known but from the knowledge of the lithology, it can be primarily concluded that the hydraulic conductivity is very low.
Literature: Gravesen et al., 2004; Knudsen, 1984, 1985; Knudsen & Lykke-Andersen, 1982; Knudsen & Penney, 1987; Lykke-Andersen, 1990.

9.4 Late Glacial marine clay deposits

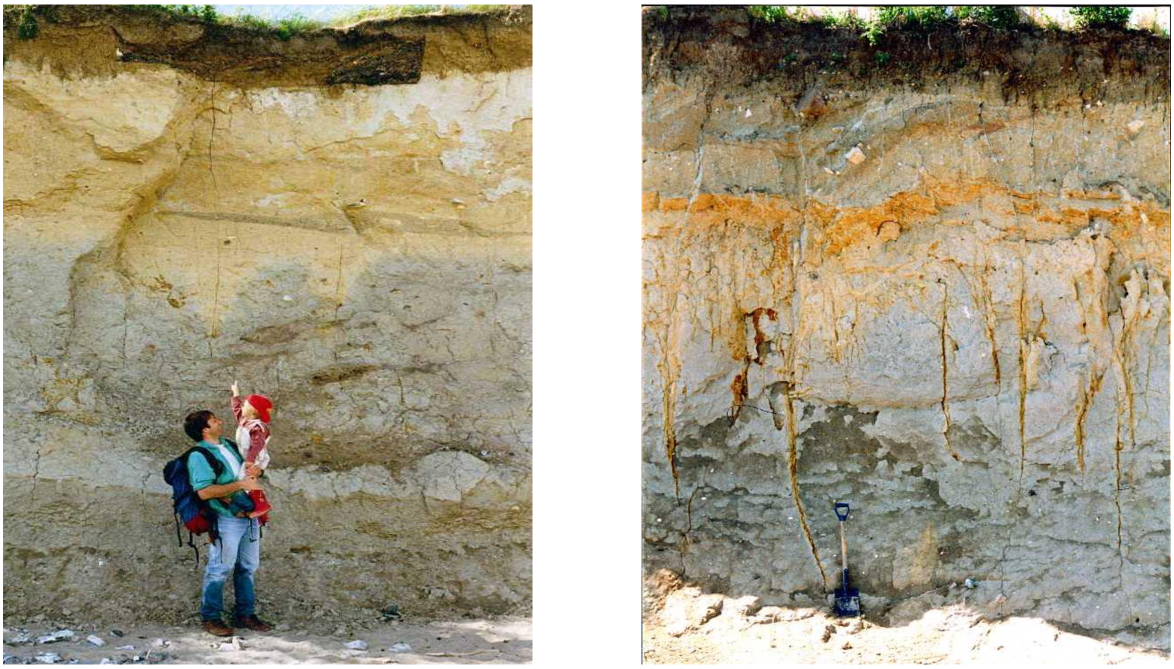
Age: Late Pleistocene (Late Weichselian)

Lithology: The Late Weichselian marine clay (Yoldia clay) in Vendsyssel, northern Jylland, is a silty or sandy, sometimes fat grey clay with thin silt and sand strikes and a few gravel grains. It often contains black spots of organic matter and marine shells.

Towards the south, in the Limfjord area, the Yoldia clay is laminated and without shells (non-fossiliferous) (Ålborg Clay, Berthelsen, 1987).
Thickness and distribution: The deposit is found in northern Jylland north and immediately south of Limfjorden. The thickness is 5–15 m. in north-eastern Vendsyssel but in the Ålborg area, it can reach thicknesses of 25–30 m. The clay deposits often rest on glacial deposits and in some areas just above the chalk (Andersen & Sjørring, 1992).
Literature: Andersen & Sjørring, 1992; Berthelsen, 1987; Fredericia, 1989.

9.5 Mineralogy and geochemistry

The mineralogy of the glacigene and marine deposits is mainly investigated in the tills, focusing on the clay-silt component and the clast component in the gravel fractions. Only few analyses are found for the more fine-grained sediments.
The content of heavy minerals in the Weichselian units in eastern Denmark is dominated by hornblende, epidot, garnet, magnetite, ilmenite and ilmenite-hematite. The units can be related to and separated into two heavy mineral provinses: a northern and a southern province (Holm, 1981).
Analyses of the clay mineral content in clayey tills and meltwater clays from localities in Fyn and Sjælland is carried out by Ernstsen (1998). The composition and transformation of clay minerals is related to chemical conditions in the lower unweathered, $CaCO_3$-rich, grey coloured, reduced zone and the upper weathered, $CaCO_3$-poor, brownish coloured, oxidized zone. The altering pattern shows transformation of chlorite and illite to smectite and vermiculite, which is in accordance to studies performed in relation to investigations of agricultural conditions.
The chemistry of the Quaternary sediments is analysed in several investigations, mainly focusing on heavy metals, trace elements and radioactive elements (Binzer, 1974, Langtofte, 1994, Gravesen et al., 1996, 1999, Gravesen & Jakobsen, 2010).



a b

Figure 9. Clayey till profiles in a coastal cliff at Gedser Odde, Falster. Two examples of the redox interface, i.e. the boundary between the oxidized yellow till and the reduced grey till. a. An undulating redox interface, b. The redox interface follows the deep fractures from the yellow brown till into the grey till. (Photos: K.E.S. Klint).

9.6 Hydrogeology and hydraulic parameters

Clay till deposits: Clayey tills comprise a significant proportion of the Quaternary deposits in Denmark. Due to the apparent impermeable nature of the till matrix, these substrates were believed to protect underlying aquifers from migration of contaminants. However, several recent studies indicate that clayey tills contain complex fracture systems, which extend deep into Quaternary deposits (e.g., Fredericia, 1990; Klint, 2001). Near-surface bioturbations together with intersecting fractures of varying orientations form a spatially complex flow network in many till sequences, see Fig. 9 (Sidle et al., 1999). The possibility (risk) that a contamination migrates to the groundwater is drastically increased if the preferential flow pathways are connected over long vertical distances (Jørgensen and Fredericia, 1992; McKay and Fredericia, 1995; Brüsch and Jacobsen, 1995; McKay et al., 1999; Jacobsen and Klint, 2001; Nilsson et al., 2001). Indications exist (from pump tests) that relatively extensive clay layers are penetrated by hydraulically conductive fractures to depths of many meters (Harrar, 2004; Cartwright, 2001; Jones, 1999). Field experiments have revealed that transport of a contamination is enhanced significantly if fractures are present (Jørgensen et al., 2002; Broholm et al., 2000; Harrar et al, 2007). Embedded sand lenses are often observed in the shallow portion of till deposits (Haldorsen and Krüger, 1990; Troldborg et al., 2008; Pedersen, 2004), although their extent, orientation, and frequency are not well documented. A large number of locations have been characterised concerning fracture distribution and hydraulic properties (Fig. 10). The hydraulic conductivity varies with depth. Above the redox transition, the bulk hydraulic conductivity decreases with 2-4 orders of magnitude from 10^{-4} m/s at 1-2 meters depth to 10^{-7} m/s at 3-5 meters depth. In the unweathered till, the hydraulic conductivity varies unsystematic with k values between 5–6 orders of magnitude (10^{-4} to 10^{-9} m/s). Matrix permeability is typical ranging between 10^{-9} - 10^{-10} m/s.

1. Silstrup (*)
2. Farre (*)
3. Grundfør (*)
4. Hinnerup (*)
5. Estrup (*)
6. Ringe (*)
7. Lillebæk (*)
8. Slæggerup (*)
9. Rantzausgade
10. Avedøre (*)
11. Englandsvej
12. Kamstrup
13. Syvbæk
14. Havdrup (*)
15. Haslev (*)
16. Flakkebjerg (*)
17. Faardrup (*)
18. Skælskør (*)
19. Skuderløse
20. Gedserodde
21. Foulum (*)
22. Aversi (*)
23. Højbakkegård
24. Snubbekorsgård
25. Mammen (*)
26. Gjorslev (*)
27. Højstrup (*)

Figure 10. Map of the locations where fracture characterization has been performed and some locations where saturated hydraulic conductivity/matrix conductivity has been determined using various test methods. The asterisks mark the areas where the tills are described according to Klint (2001). (From Klint in Gravesen & Rosenberg, 2009).

Meltwater and marine clay deposits: No investigations have been reported on characterization of the hydraulics in the meltwater and marine clays.

10. GENERAL HYDROGEOGICAL CONDITIONS

10.1 Groundwater formation, flow and chemistry

In Denmark, 98 % of the drinking water is groundwater pumped up from the groundwater reservoirs. It is a major task for the Danish Water Works to deliver enough drin-king water of the right healthy quality to the Danish population. Therefore, the protection of the groundwater quality is a very important issue and pollution from point sources and diffuse sources is forbidden in the recharge areas of high quality groundwater (see Fig. 11).

Groundwater is formed when net precipitation (precipitation minus evaporation) infiltrates the soil below ground surface and percolate through the unsaturated zone to the saturated zone, the groundwater.

The directions of the groundwater flow will be towards the recipients: Streams, lakes, the sea, springs or water borings. The distance between the groundwater divide and the recipients can be rather long.

The groundwater chemistry is depending on a combination of the composition of the rainwater, chemical reactions with the reservoir sediments and rocks and any pollution components from point and/or diffuse sources. The chemical composition is important in relation to possible reactions with constructions (especially saltwater) and possible reactions with radioactive pollution from a disposal.

10.2 Areas of special drinking water interests (OSD)

The Danish Drinking Water Authorities have become aware that it is important to protect the groundwater, if the Water Works should continue to pump clean drinking water. It is the Environmental Centres (former counties) responsibility to map the groundwater resources and to plan the protection of the groundwater interests. The planning is based on two criteria: First, to make sure that the necessary quantity of clean groundwater can be abstracted in the future. 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 in Denmark have designated areas of major groundwater aquifers, so-called OSD-areas. OSD stands for "Areas of special drinking water interests”.

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 (Fig. 11).

The Environmental Centres designation of the areas is based on many years' mapping of the subsurface geological layers. It gave an overview of the amount of water that can possible be pumped up and how well the water quality is.

In the OSD areas, the groundwater primarily supplies drinking water to the population. Therefore, groundwater is and will be effectively protected against contamination. This means, that the Environmental Centres/Regions must remove old contaminations that threaten groundwater. And not least, the Environmental Centres/Regions must ensure that there will be no new contamination of the OSD areas.

The size of the individual OSD areas must be large enough to ensure that they can meet our current *and future* consumption of drinking water. Moreover, in the designation of the OSD areas, it was ensured that the groundwater flows away from the areas. So, there is no possibility for an inflow of contaminated groundwater from neighbouring areas.

In total, around 35 % of Denmark is appointed as OSD areas. In Jutland, it has only been necessary to identify about a quarter of the area, while there is a need for much larger areas on the islands. This is due to a higher net-precipitation, a lower evaporation, a larger groundwater formation and a smaller population in Jutland, compared to Fyn and Sjælland.

The Environmental Centres must also take the EU protected nature areas into account (NATURA 2000). Therefore, the reclamation is not allowed to reach a level that course streams and wetlands to dry out. Animals and plants also need and have a right to water. Finally, water is needed for irrigation and industrial use.

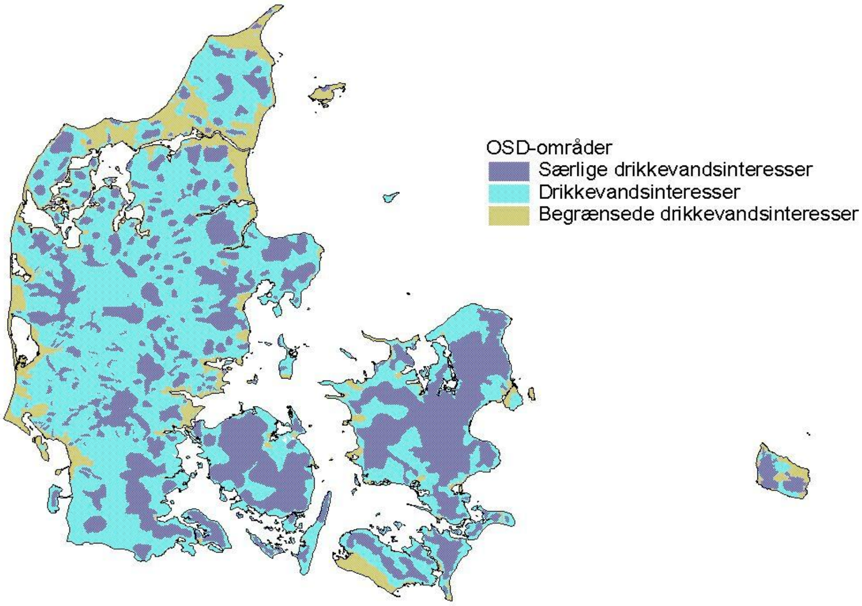


Figure 11. Digital map of the drinking water interest areas in Denmark (OSD and OD areas). Legend: Purple: Areas of special drinking water interests (OSD). Light blue: Areas with drinking water interests (OD). Olive: Areas with limited drinking water interests.

10.3 Need for further data concerning safety modelling

In the report from 2007 (Indenrigs- og Sundhedsministeriet, 2007), the need for quality data concerning safety modelling is emphasised. The present selection of potential localities for radioactive waste storage is based on existing knowledge, which may be insufficient for a modelling that is suitable to secure storage for a period of a least 300 years. In particular, the knowledge concerning residence time and hydrochemistry of groundwater in low permeable geological formation is limited, since most of the research has focused on aquifers. Studies on groundwater in low permeable formations have been performed, but are often related to contaminated sites, focusing on the spreading of specific contaminants, rather than accurate characterisation of the general hydrochemistry and residence time.

When collecting additional data on hydrochemistry and residence time at a specific site for safety modelling great care should be exercised in order to obtain representative samples of groundwater. This may require improved well construction, e.g. Wassenaar and Hendry (1999) and/or extraction of pore water from argillaceous formations (Pearsons et al., 2003 or Sacchi et al., 2001). Residence time may be obtained by isotopic analyses. The appropriate ones may be decided when a specific site has been pointed out.

For modelling of retardation of radio-nuclides by sorption in case of leakage of radioactive material from the stored containers, additional data on the mineralogy of the geological formation in which the waste deposit is to be established, may also be needed. The retardation modelling may either include critically evaluated empirical sorption (Kd) data (Carbol and Enkvist, 1997) or apply a more basic approach to sorption by the Surface Complexation Method (Siegel and Bryan, 2004).

11. CLIMATE, CLIMATE CHANGE AND SEA LEVEL

The Danish climate is primarily controlled by the location of the country in the periphery of the European continent, at the border of the North Sea and close to the Atlantic Ocean, in the belt of the westerlies. Therefore, the climate is a temperate, marine west-coast climate, characterized by cool summers (mean temperature around 16 ^{o}C) and not very cold winters (mean temperature around 0.5 ^{o}C). The annual mean temperature is c. 8 ^{o}C, which is very mild for this latitude and caused be the proximity to the Gulf Stream, bringing warm water towards the north. It is often windy – especially during winter months where cyclonic breezes/storms are frequent. Owing to the westerlies, the precipitation falls throughout the year, but the geographical distribution is marked by regional differences in the amounts, see later.

11.1 Climate parameters

When focusing on the subject: 'identification and selection of localities, potential for radioactive waste storage at the ground surface or down to 300 meters depth (therefore either above or below the groundwater level) and for a period of at least 300 years, the all-important climate "factor" is the water, or – more specific – the amount of net precipitation, which might infiltrate the ground and increase the water flow in the subsoil and raise the level of the groundwater as well. The net precipitation is the part of the precipitation that does not evaporate.

For these reasons, the following text focuses on precipitation and evaporation, while temperature and wind are given less attention and other climate parameters are not mentioned at all.

11.1.1 Precipitation in Denmark

Large uncertainties are attached to measuring of precipitation: Wind speed is the dominant environmental factor that leads to an under catch of precipitation; wetting losses occur when precipitation collects on the inside walls of the gauge and evaporates or sublimates without being recorded; losses due to evaporation of precipitation between the measurements; operational problems of weighing gauges; errors due to blowing and drifting snow, etc. Therefore, when using precipitation data, it is important to know, whether the actual values are observed or corrected precipitation data. As seen in Table 1, the corrected mean yearly precipitation for the period 1961-90 is c. 16 % higher than the observed data.

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Corrected (1961–90)*)	69	46	56	48	55	63	74	74	82	87	92	79	826
Observed (1961–90)*) **)	57	38	46	41	48	55	66	67	73	76	79	66	712
Observed (1931–60)**)	55	39	34	39	38	48	74	81	72	70	60	55	664
Ratio **)	1.04	0.97	1.35	1.05	1.26	1.15	0.89	0.83	1.01	1.09	1.32	1.20	1.07

*Table 1. National average precipitation (mm) in Denmark in the standard periods 1931-60 and 1961–90 (observed and corrected). Ratios above 1 indicate an increase in observed precipitation from 1931-60 to 1961-90. (*) After Jensen & Jensen, 2001; and **)Frich 1990 in: Frich et al. 1997).*

The precipitation falls throughout the year but the distribution is marked by some seasonality. November and October are the wettest months of the year in the western part of the country, but in the eastern part, July and August are the wettest months. February and April are generally the driest months of the year in all parts of the country. Taking the length of the month into account, April is generally the driest (Frich et al., 1997).

The distribution of the mean annual precipitation is marked by large regional variations, see Fig. 12. Maximum precipitation (> 900 mm/year) is found in the south-western part of Jylland, immediately west of the Jutlandish ridge (orographic rain). Other local maxima are found in high lying areas. A distinct minimum (< 500 mm/year) is found in the Storebælt area. The precipitation is generally higher in Jylland compared to the eastern parts of the country.

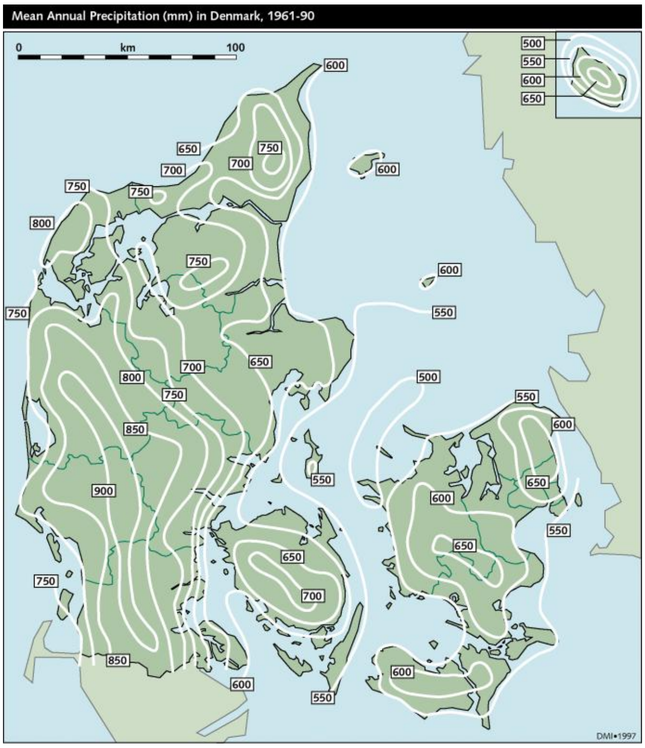


Figure 12. Mean annual precipitation in Denmark, 1961-90. The map is based on observed data from 300 stations. It has been produced by visual interpolation, taking into account the topography of the country and the shelter conditions of individual stations (Frich et al., 1997).

Beside a geographical pattern in the distribution of precipitation, the amount of precipitation varies through time, see Fig. 13. Beside some very large variations from year to year, the data show a clear tendency toward more and more precipitation. Comparing the two youngest standard periods, 1931 –1960 and 1961 – 1990, respectively, an increase in mean yearly precipitation of 48 mm (c. 7.2 %) is found (Table 1). When comparing the mean yearly precipitation of the newest period, 1991 – 2009 (743 mm), to the most recent standard period 1961 – 1990 (712 mm), the increase in mean yearly precipitation is 31 mm (c. 4.5 %). Generally, the precipitation has increased in all parts of the country, see fig. 143,a and b (Cappelen & Scharling 2010).

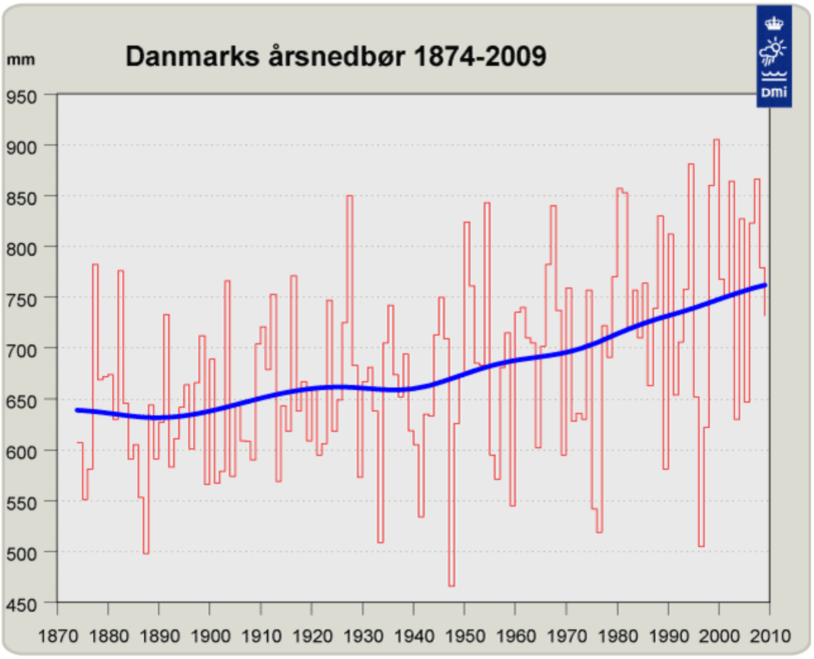


Figure 13. The total yearly precipitation in Denmark since 1874. The calculation of the values is based on a number of selected meterorological stations. The bold blue line is 9 years Gauss filtered values. (www.dmi.dk/dmi/index/klima/klimaet_indtil_nu/nedboer_og_sol_i_danmark.htm in: Cappelen 2009).

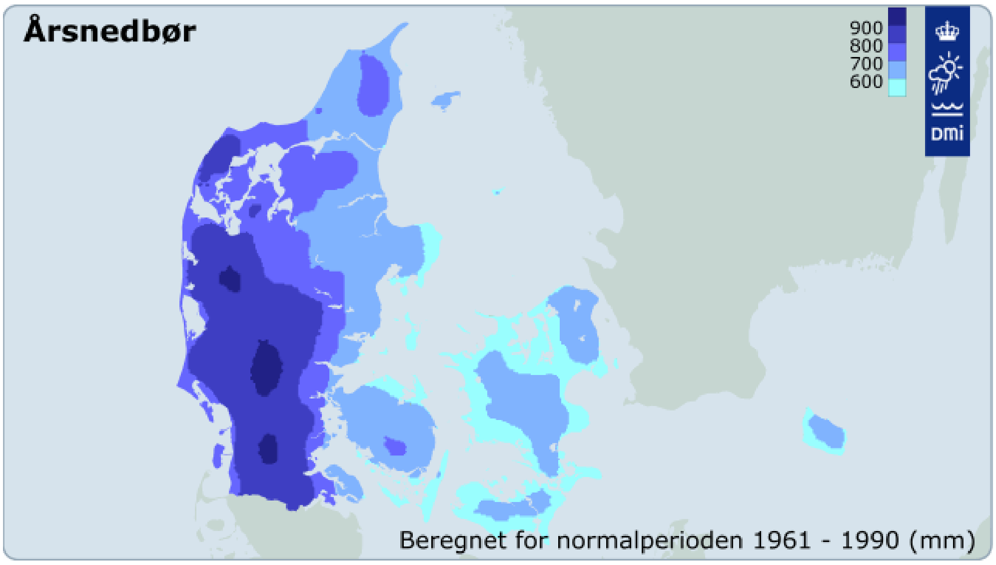


Figure 14,a. The mean yearly precipitation calculated for the standard period 1961 – 90 (mm). (Cappelen & Scharling 2010)

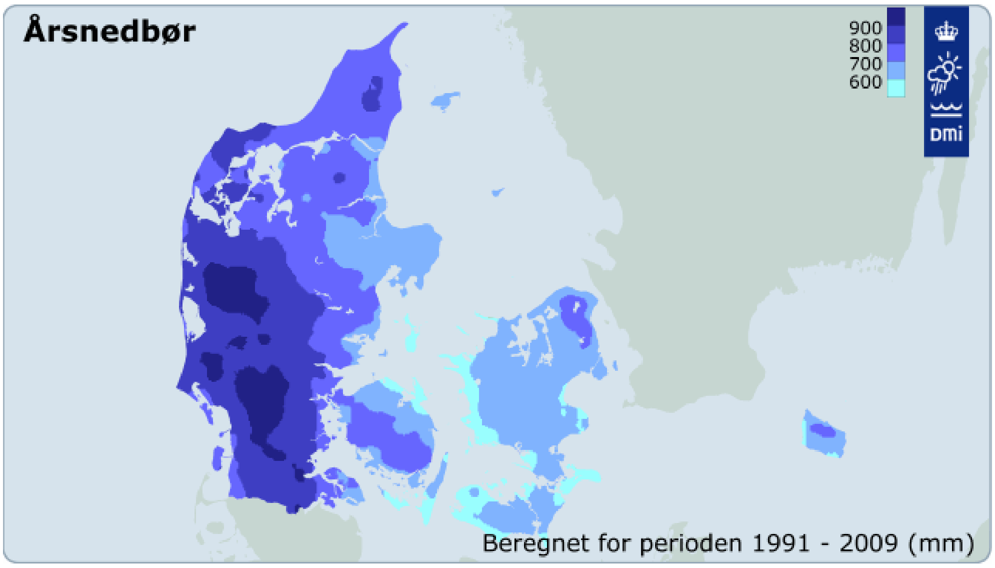


Figure 14,b. The mean yearly precipitation calculated for the period 1991 –2009 (mm). (Cappelen & Scharling 2010)

11.1.2 Future changes in precipitation

The climatic changes have already caused changes in the precipitation pattern. All analyses indicate that this development will continue in the future. The number of “rain events” diminishes, but the extreme rain events will become substantial more powerful (Arnbjerg-Nielsen 2008).

By means of global and regional climate models, DMI has calculated the overall development for the Danish climate in 2100 compared to the 1990 situation for the A2- and B2 scenarios. A moderate increase of the winter precipitation (120–140 % of the present precipitation) and presumably a minor reduction of the summer precipitation (85–90 % of the present precipitation) are expected. A tendency toward more episodes of very intense precipitation is also expected, primarily in autumn. Moreover, the size of the heaviest “24-hour-preciptitation” will increase with 20 % or more. In spite of this, the soil moisture will be reduced, especially during spring and summer months and we must expect longer periods without precipitation in the growth season resulting in higher drought risk (DMI 2010) and a higher number of situations with a large surplus of water – “flooding-situations” – during autumn and winter.

11.1.3 Evaporation

The actual evaporation on a given place is depending on the amount of precipitation, the temperature, soil type, soil moisture, vegetation, wind etc. Long-time series of measured actual evaporation (E_a) do not exist, neither in Denmark nor abroad.

Indirectly, the actual evaporation can be calculated by means of the water balance equation:

$P = E + R_o + R_u + \Delta M$

P = Precipitation (rain, snow, hail). E = Evaporation (incl. transpiration). Ro = Runoff, overland flow (e.g. stream; watercourse). Ru = Runoff, underground outflow (e.g. groundwater outflow). ΔM = Changes of water magazines: infiltration to the soil; recharge or surplus of soil water, recharge or surplus of groundwater. The actual amount of water in the magazine changes from day to day as a result of three processes: precipitation, actual evaporation and seepage to the subsoil. During longer periods, a year or more, $\Delta M = 0$, on the assumption that the climate is stable.

Using this method implies an intimate knowledge of the size of the other parameters in the equation, which means that the method is practically unsuitable for many purposes. Instead, the evaporation is calculated as the potential evaporation, Ep, typically based on a modified Penman-method, including parameters such as slope of the saturation vapour pressure curve, net irradiance, density of air, heat capacity of air, vapour pressure deficit, etc. The distribution of the potential evaporation in Denmark 1971–98 is shown in Fig. 16. The calculations were based on a modified Penman-method (described in: Mikkelsen & Olesen 1991).

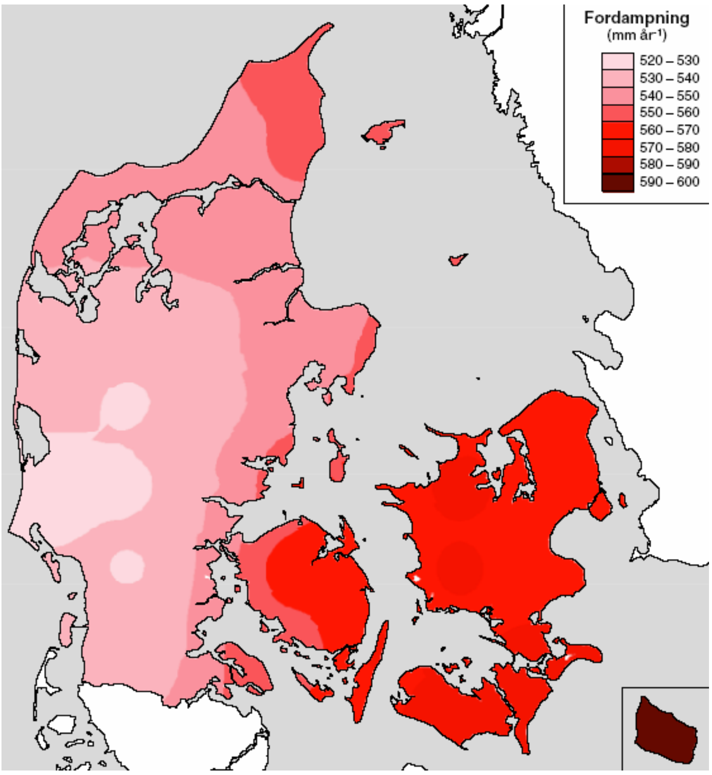


Figure 15. Yearly potential evaporation (mm/year) in Denmark. From Ovesen et al. 2000.

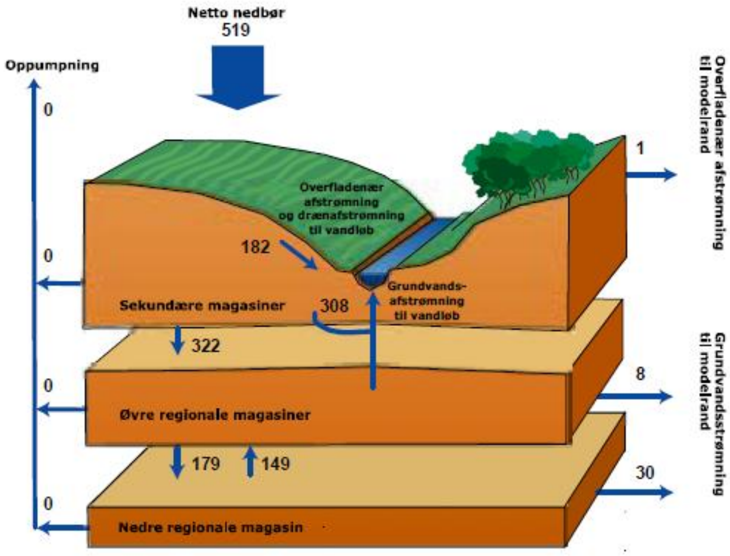
The potential evaporation in Denmark range from c. 520 mm/year in the western part of Jylland, rises towards east, to 560-590 mm/year on Sjælland and Lolland-Falster and culminates on Bornholm (590-600 mm/year). One of the main reasons for this distribution is the Quaternary surface deposits. In the western part of Jylland, the deposits are very sandy. In this part of the country, a large amount of the precipitation percolates through the ground to the groundwater or run off to the streams, resulting in relatively low soil moisture values. The situation is opposite in the eastern part of the country, where the soils have a higher content of clay. For the country as a whole, the actual evaporation is less than the potential evaporation from c. May to September, owing to a deficit in soil moisture. The remaining part of the year, the actual evaporation equals the potential.

As mentioned above, the evaporation (potential as well as actual) is depending on precipitation and temperature as the main controlling factors. In spite of a future increase in precipitation, the soil moisture will be reduced, especially during spring and summer months and we must expect longer periods without precipitation in the growth season (DMI 2010). The reason is partly found in the character of the precipitation (as described above), partly in a temperature rise. During the period 1874–1998, the mean temperature in Denmark has risen 0.86^{o} C. The global temperature has risen between 0.3 and 0.6^{o} C since 1860 (IPCC 1995 in: Ovesen et al. 2000). So, we have experienced a higher temperature rise in Denmark, compared to the global temperature rise. This temperature rise may contribute to a higher evaporation and with that a reduced run off in the Danish streams (Ovesen et al. 2000).

11.2 The climate changes´ influence on the water circulation in Denmark

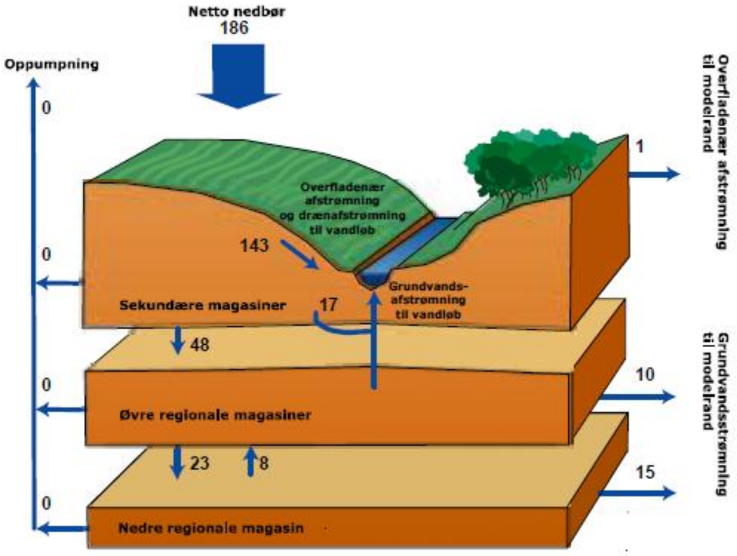
In 2006, data on how the climate changes will influence on the hydrologic system in Denmark, when the groundwater, the surface water *and* the interaction between these two domains are taken into consideration, were still not published (Sonnenborg et al. 2006). The interaction between surface water and groundwater depends on the geology, why it is important to incorporate the geological composition of the subsoil into the models of the climate changes´ influence on the water circulation, the level of the groundwater, the future development of the groundwater formation and the size of the groundwater runoff (Sonnenborg et al. 2006). Sonnenborg et al. (2006) have calculated the consequences of future climate changes for two very different regions in Denmark: one area is situated in the western part of Jylland and the other area is Sjælland. “The national water resource model” (also called the DK-model) makes the basic tool for the quantifications of the climate impacts on water circulation. The actual (now) situation and the two IPCC scenarios A2 and B2 (middle high and middle low scenarios of greenhouse gases emission, respectively) have all been investigated for the “natural condition”, which excludes reclamation of groundwater. Furthermore, the now-situation and the scenario A2 - situation have both been investigated for a condition, where reclamation of groundwater is included. The latter situation will not be shown here, as a final disposal for radioactive waste will be situated outside areas with drinking water interests. Prior to running these models, a lot of assumptions and reservations have to be taken. These, the models and methods used are specified and described in Sonnenborg et al. (2006).

In all situations depicted below, the thick blue arrows indicate net precipitation; the thin blue vertical arrows illustrate water exchange between secondary magazines, upper regional magazine and lower regional magazines plus groundwater runoff to streams; oblique arrows indicate near-surface runoff to streams and the horizontal blue arrows (pointing right) indicated near-surface and groundwater runoff to model edge (e.g. the sea). Arrows pointing left indicate reclamation of groundwater, which is zero in all depicted situations. All figures are mm/year.



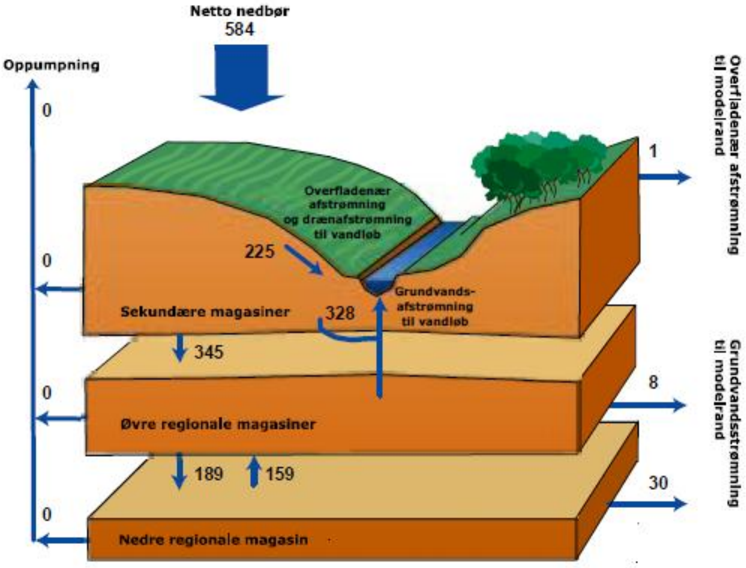
Actual situation, Western Jylland.

All values represent yearly mean values for the period 1990–2004.

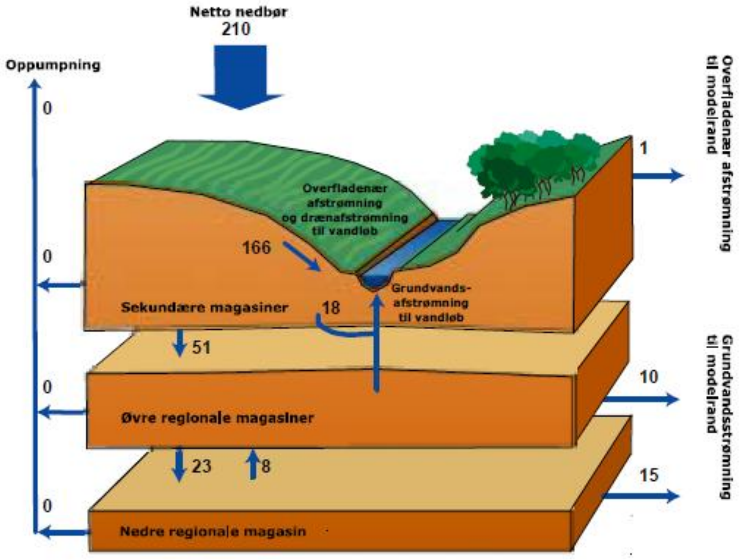


Actual situation, Sjælland.

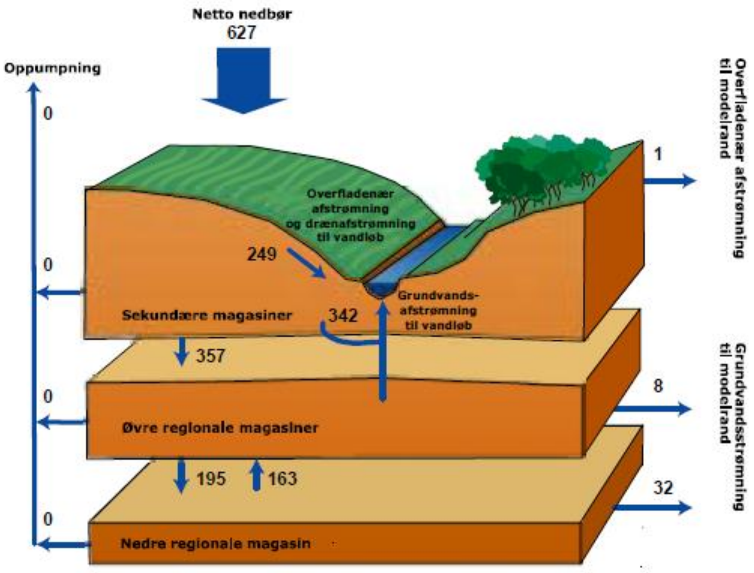
All values represent yearly mean values for the period 1990–2004.



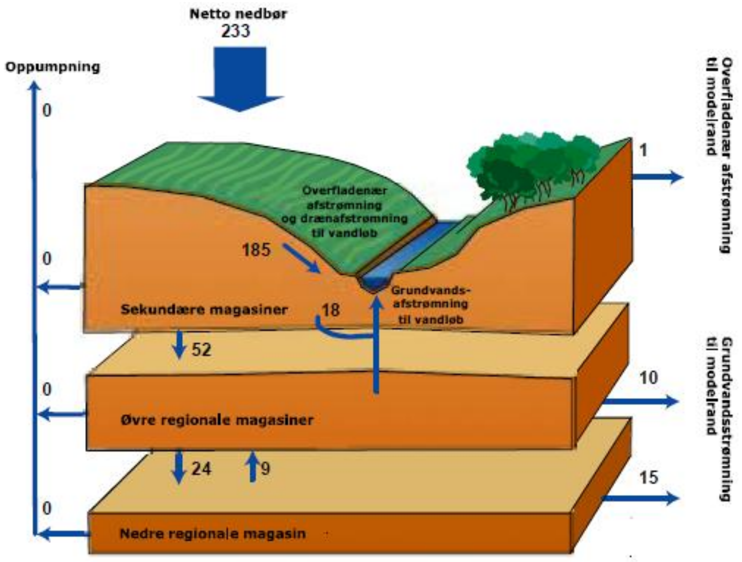
A2-scenarie, Western Jylland.



A2-scenarie, Sjælland.



B2-scenarie, Western Jylland.



B2-scenarie, Sjælland.

Figure 16 illustrates the actual water balance in western Jylland (left) and Sjælland (right), uppermost situation, and the climate changes´ influence on the water balance in an A2-scenarie (middle situation) and in a B2-scenarie (bottom). From Sonnenborg et al. 2006.

The actual situation (Fig 16, uppermost) clearly demonstrates marked regional differences in the water balance between western part of Jylland and Sjælland. The differ-

ences in net precipitation are caused by differences in precipitation as well as evaporation. The differences in net precipitation plus marked differences in the geology results in a much larger groundwater formation and runoff in Jylland compared to Sjælland.
The net precipitation rises in both A2- and B2 scenarios, but the runoff to the sea is relatively unchanged. So, the increased precipitation results in more runoff via the streams. In the B2-scenare, in western Jylland, the groundwater formation is markedly increased and a considerable flow in the upper as well as lower regional magazines is generated. The same tendencies are seen in the A2-scenarie, although the absolute changes are smaller. The situation on Sjælland is quite different as the increase in net precipitation has almost no effect on (the deep) groundwater formation. The increased net precipitation results (almost only) in an increase of the runoff via drains and surface runoff (Sonnenborg et al. 2006).

To conclude: it is difficult and subjected to large uncertainties to forecast the size of the subsurface water flow as well as the groundwater formation etc. on a given location without an intimately knowledge of the climate parameters (especially net precipitation) and – not the least, the geological composition of the subsoil.

11.3 Sea level rise, coastal erosion, flooding and salt water intrusion

Rising sea levels inundate wetlands and other low-lying lands, erode beaches, intensify flooding, and increase the salinity of watercourses and groundwater tables through salt-water intrusion.

Projections suggest that the rate of sea level rise is likely to increase during the 21st century, although there is considerable controversy about the likely size of the increase. This controversy arises mainly due to uncertainties about the contributions to expect from the three main processes responsible for sea level rise: thermal expansion, the melting of glaciers and ice caps, and the loss of ice from the Greenland and West Antarctic ice sheets (www.climate.org – see this homepage or IPCC 2007 for a thorough description of uncertainties). Moreover, the rate of sea level rise varies globally and regionally.

The global sea level rise is some 18 – 38 cm for the low scenario and 26 – 59 cm for the high scenario until 2100. The processes of the climate system means that the sea level will continue to rise for several hundreds of years after the atmospheric content of greenhouse gases has stabilized. If the content of greenhouse gases is stabilized at the level reached in 2100 after the lowest scenario, the temperature will increase another ½ degree after 2100, which will lead to a further sea level rise of 0,3 – 0,8 meter until 2300, solely because of the thermal expansion of the water. Thereafter, the rise will slow down (DMI, 2010).

	Best estimate ^{o}C change in 2090-2099	Likely ^{o}C interval in 2090-2099	Sea level change (m), calculated for 2090-2099
Constant year 2000-Concentration	0.6	0.3 – 0.9	
B1-scenarie	1.8	1.1 – 2.9	0.18 – 0.38
A1T-scenarie	2.4	1.4 – 3.8	0.20 – 0.45
B2-scenarie	2.4	1.4 – 3.8	0.20 – 0.43
A1B-scenarie	2.8	1.7 – 4.4	0.21 – 0.48
A2-scenarie	3.4	2.0 – 5.4	0.23 – 0.51
A1F1-scenarie	4.0	2.4 – 6.4	0.26 – 0.59

Table 2. Projected global mean warming and sea level changes at the end of the 21. century for different climate models. The calculations of sea level changes do not include the uncertainties of the feedback mechanisms in the carbon cycle (DMI 2010).

Beside the sea level rise caused by thermal expansion, another rise must be added because of a changing wind pattern. A tendency toward more frequent wind from westerly directions and a small increase in the storm activity over Denmark and adjacent waters will cause a maximum sea level rise from 1990 to 2100 at the West coast (in the A2 scenario) of 0.7 to 1.05 meters which is the sum of 0.3 meter from changes in wind pattern plus 0.4 – 0.75 meter of global and regional sea level rise (DMI, 2010).

The hydrography of the interior Danish waters is controlled by the water exchange between the Baltic and the North Sea, which in turn is connected to the Northern Atlantic. Persistent westerly winds force the water from the North Sea into Kattegat and the Belts and produce high sea levels. Correspondingly, easterly winds produce low sea levels. Meteorologically induced sea level variations can range between +1.9 and – 1.5 m DNN (Danish Ordnance Datum) on the east coast of Jutland (Christensen et al., 1985; Cappelen et al., 1989). The expected sea level rise should be added to this level. It is most likely that the expected change in the wind pattern (mentioned above) will cause periods of high sea levels to occur more often and to a higher level.

When locating a final disposal for radioactive waste, it is important to consider any future problems concerning problems from coastal erosion and salt-water intrusion.

12. PRIMARILY EVALUATION OF THE SEDIMENTS AND ROCKS

12.1 Criteria for selection of localities

With respect to sediment or rock type, the main geological, hydrogeological and hydrochemical criteria for selection of an area or locality are the following (Indenrigs- og Sundhedsministriet, 2007):

1. The disposal should be situated in an area with homogeneous geological conditions. It should be demonstrated that these conditions will be found with a high degree of probability at the selected sites. The geology of Denmark is in many areas relatively heterogeneous. However, it is the goal to find continuous and homogeneous sediments or rock layers.
2. The geological deposits shall contribute to isolation of the radioactive waste. This is most effective if the disposal is underlain or surrounded by tight layers such as e.g. clays, silts, limestone or basement rocks.
3. To restrict the water flow from the disposal it will be appropriate if the disposal is sited in low permeable deposits.
4. The disposal shall be placed at longest possible distance from groundwater aquifers. The streaming conditions of the surrounding deposits or rocks must be low.
5. The disposal shall not be located in an area of special drinking water interest (OSD areas).
6. The groundwater conditions shall contribute to dilution of radioactive components that have leaked from the disposal.
7. The sediments, rocks and groundwater shall promote sorption of leaking radioactive components.
8. Geological processes on the earth surface may not be able to influence on the security of the disposal.

The description concept will follow Gravesen et al. (2010):

a. Geological conditions
a1. General setting
a2. Surface geology and profiles
a3. Boreholes
a4. Sediment and rock characteristics
a5. Tectonics and structures
a6. Seismic activity
a7. Geological and structural models
a8. Ground stability

b. Hydrogeological conditions
b1. Drinking water areas
b2. Groundwater characteristics
b3. Reservoir and cover sediments and rocks
b4. Geo- and hydrochemical conditions

c. Ground surface conditions
c1. Terrain and topography
c2. Surface processes
c3. Climate and climate changes
c4. Restrictions and limitations
d. Summary of area conditions
e. Final remarks
f. Literature

During an evaluation of the sediment and rock types described above, it is necessary to recognize the existing restrictions of the areas. The special drinking water areas will be avoided in the evaluation process but also the NATURA 2000 areas (Habitat and bird protection areas), nature and landscape protection areas and protection areas for ancient monuments are important factors in the process.
It is areas in the open landscape, which will be evaluated and selected for potential waste sites. Whereas areas in or near cities, buildings and future areas of city development are avoided.
As a first approximation, all the sedimentary deposits and rocks within the special drinking water areas (OSD, see Fig. 11) will be excluded from a list of potential disposal sites.
Following this procedure, approximately 35 % of the land area will not be evaluated any further.
In the remaining areas, the selection criteria (Chapter 11.1) point towards evaluation of geological conditions considered and based on the criteria in this chapter. Moreover, the relations of the descriptions of the sediments and rocks in chapter 3-9 and the general hydrogeology in chapter 10 are included.

It is important to mention that the areas and locations probably will consist of a combination of at least two sediment and/or rock types because most of the country has a top layer of Quaternary clays. The basement of Bornholm makes an exception. Potential combinations could probably be:
Quaternary clayey till above:
- Quaternary meltwater or interglacial clay,
- Tertiary fine-grained and sticky clay,
- Cretaceous and Paleogene limestone or chalk
- Precambrian basement rocks.

From this, it follows that areas with sand and gravel sediment from the terrain surface to large depth are excluded.

12.2 Preliminary evaluation of sediments and rock types

Following the considerations in chapter 11.1, the areas below (including several possible locations for waste disposal sites) are selected for further investigation.

The Precambrian basement rocks of Bornholm could be host rocks for the disposal. The rocks are situated and exposed near the ground surface and covered by thin layers of Quaternary deposits. Outside the OSD areas, rocks in northern, south-western and central areas will be analysed further. The rocks will be most suitable if they only hold a limited amount of major fractures or fault zones and if they are only weakly weathered in the top. The rock types for further evaluation will be: Hammer Granite, Vang Granite, Rønne Granite, Bornholm gneiss, Paradisbakke Migmatite and Alminding Granite.

In the Roskilde Fjord area around Risø, a combination of Paleocene clays, meltwater clay and clayey till could be interesting. The area is partly included in the OSD area in North Sjælland but owing to the location of Risø close to the Roskilde Fjord and therefore the possibility of a short transport of the waste, the area is included in the evaluation.

On south-eastern Sjælland and Møn, areas close to the shore where limestone and chalk deposits are covered by thin layers of clayey till can be interesting. These areas have limited drinking water interests.

In central and western Sjælland, only few areas are found outside the OSD areas but combinations of several units above each other are interesting: Eocene clay, Paleocene clay, meltwater clay and clayey till. Areas in western Sjælland with Eocene and Paleocene clays overlain by Quaternary clays and in central Sjælland with clayey till above Paleocene clay will be evaluated, but only for the locations situated outside the OSD areas.

On Falster, Lolland, Tåsinge and Langeland, plastic clay from the Holmehus Formation, Æbelø Formation, Ølst Formation and Røsnæs Clay Formation belonging to Paleocene and Eocene occur on the southern parts of the islands. The areas are situated close to the coasts and outside the OSD areas.

Only a few interesting areas are found on the island of Fyn. The deposits on the central part just south of the OSD areas consisting of ice-lake melt-water clay and tills and areas on western Fyn consisting of Eocene clays and clayey tills will be evaluated.

In eastern Jylland, areas between Fredericia and Vejle (close to Lillebælt) and between Vejle and Hedensted are interesting. Paleocene, Eocene, Oligocene and Miocene deposits are found beneath a thin Quaternary cover. These areas only hold a few groundwater interests.

In southern and western Jylland, the Quaternary Late Elsterian-Holsteinian marine clay as well as the Miocene clays from Arnum, Hodde, Ørnhøj and Gram Formations are potential areas for a disposal. The groundwater areas, OSD, are few and scattered.

Across the Middle part of Jylland, between Fur-Mors via Skive-Viborg-Sofienlund to Randers, areas with plastic clay deposits from Paleocene, Eocene and Oligocene likewise candidate as potential areas for a disposal. Only limited groundwater interests occur.

Quaternary (Elsterien-Holstenian) marine and meltwater clays are found in a large area south of Limfjorden (Jylland). It is a rather large area characterized by clay deposits of up to 100 m thickness and few OSD areas.

North and south of Limfjorden (Jylland), Late Weichselian meltwater clays occur, which have to be considered.

In northern Jylland, a site could possibly be located above Saalian tills, Eemian marine clays and Weichselian marine and meltwater clays. These areas will be evaluated further. The areas have very few OSD areas.

In addition to the areas described above, existing waste disposals in Jylland, Fyn and Sjælland could be of interest because of the existing expertise and facilities. These will be evaluated. Moreover, existing caverns in limestone deposits, such as Dagbjerg and Mønsted in the middle part of Jylland, have to be considered.

13. FINAL REMARKS

During the further process, approximately 20 areas will be selected from the larger areas mentioned in chapter 11. These areas will be shortly characterized, described, and published in a series of reports.
Based on the present report, a report on tectonics and seismic activity (Pedersen & Gravesen 2010), and several reports on the approx. 20 localities, it will be possible to select 5–10 areas (Gravesen et al., 2010).
These 5–10 areas will be further evaluated and after a detailed description, they will be reduced to 1–3 most potential localities at which e.g. detailed field work will be carried out.

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

Fractured Vang Granit from Almeløkke Quarry, Bornholm