DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/122

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report no. 1

Data, maps, models and methods used for selection of potential areas

Peter Gravesen, Bertel Nilsson, Stig A. Schack Pedersen & Merete Binderup

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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, 2007). The Minister for Health and Prevention presented the background and decision plan for the Danish Parliament in January 2009 (Minister for Health and Prevention, 2009). All political parties agreed on the plan.

The task is to locate and recognize low permeability 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 possibilities 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 the present study, the salt diapirs and the salt deposits are not included.

The task for the Geological Survey of Denmark and Greenland (GEUS) is to find approximately 20 areas potentially useful for a waste disposal. These 20 areas are afterwards reduced to 2-3 most optimal locations. At these 2-3 locations, detailed field investigations of the geological, hydro geological – hydro chemical and technical conditions will be performed.

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. The sediments and rocks are shortly described in Report no. 2. The descriptions are 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 clayey till and fine-grained 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 ground water 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, sand and gravel sediments *are* included in the final descriptions.

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

The present report briefly describes the existing data collections (including databases, maps and models), that are used during the work of selection of *ca.* 20 potentially suitable areas. Most of the information is stored in GEUS databases: Location of boreholes, borehole data, rock sediment and ground water compounds, maps, geophysical data and much more, but information is also collected from other institutions.

The methods are described in more details (chapter 6) and this description is the directly background for the selection process, the characterisation of the 20 areas and for the final selection of the 2 or 3 most potential sites.

2. DATA AND DATABASES

2.1 Distribution of rocks and sediments, environment and age

The basic information for the selection of potential areas is an abundant and extensive amount of published papers, books, maps, reports, archives and databases. An example is shown in Fig. 1. A large amount of Danish geology is published in the publication series of the Geological Survey of Denmark and Greenland (GEUS) and the Bulletin of the Geological Society of Denmark (DGF) but internal GEUS reports and reports from local counties, municipalities, regions, scientific institutions and universities also make up a valuable source of material. Publications in international periodicals are of course also a part of the basic information.

From all these information sources it is possible to describe the relevant geological and stratigraphical framework of Denmark although some areas of Denmark are only sparsely covered by data and publications.

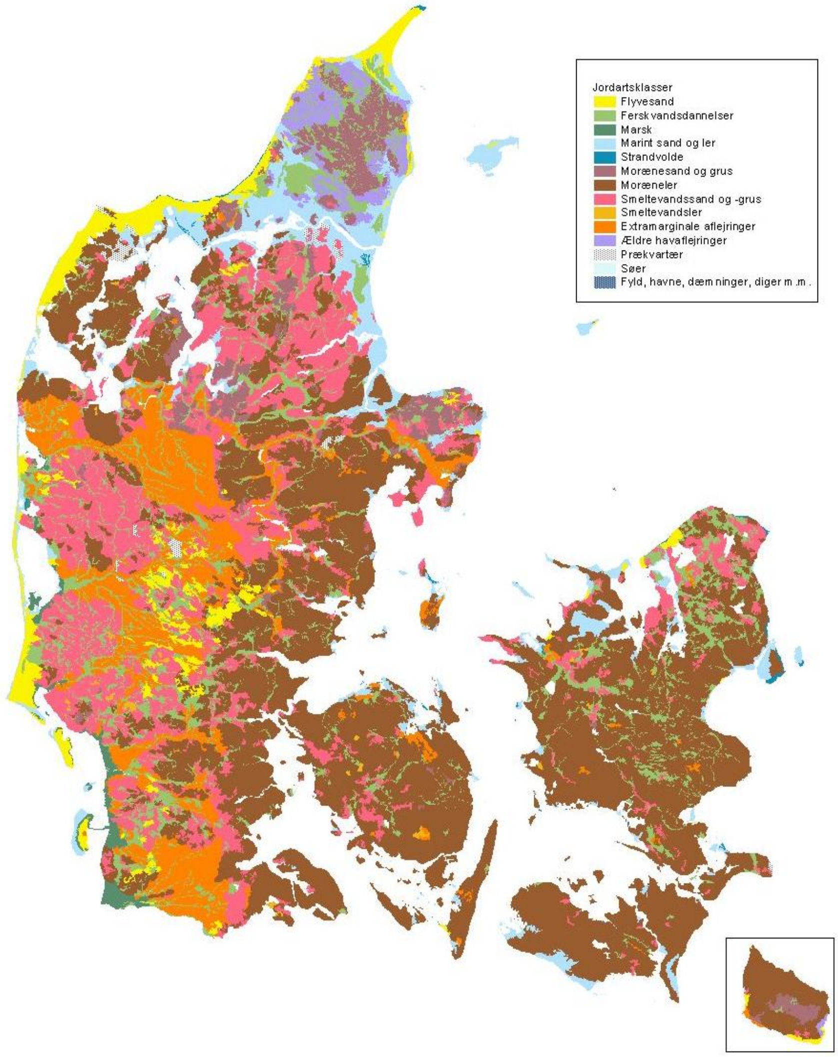
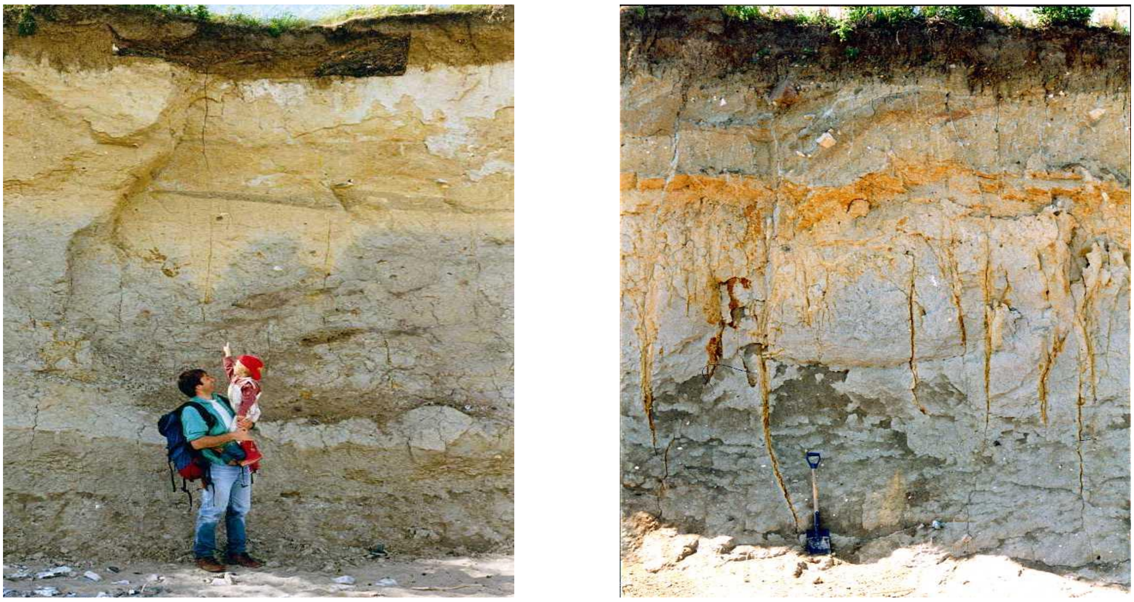


Figure 1. Example of a Danish map: The map of the Quaternary surface deposits. Original scale: 1:200.000.
Legend: Brown: clayey till. Light brown: sandy till. Red: melt water sand and gravel. Orange: sandur sand and gravel. Purple: Late glacial marine deposits. Light blue: Holocene marine deposits. Green: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

2.2 Field investigations

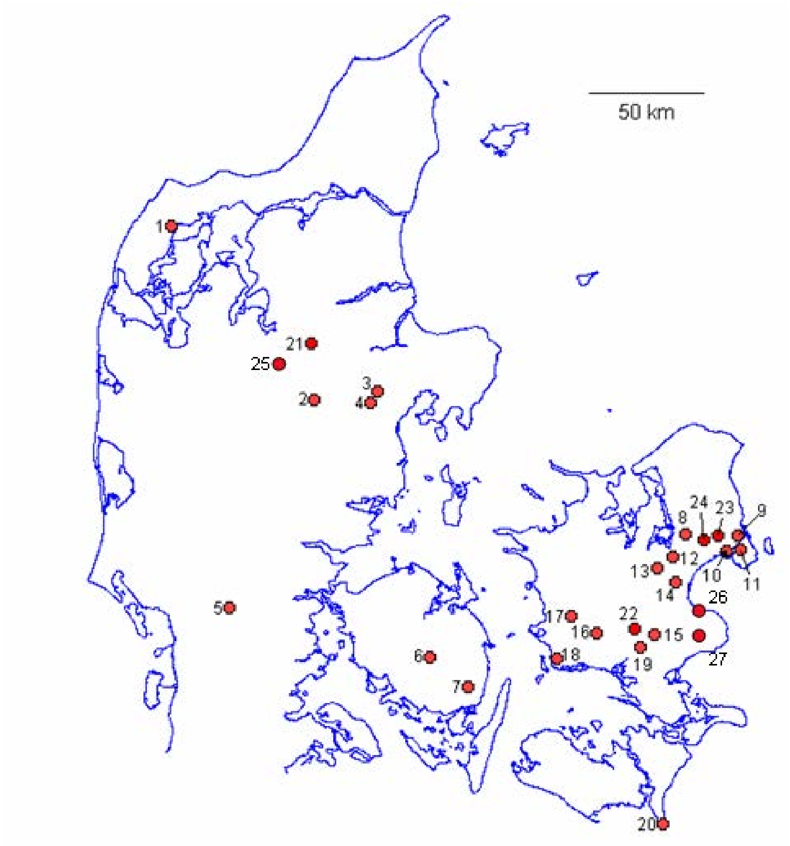
Most of the field investigations are carried out by excavation of an area (Fig. 2) or by studying of natural exposures (coastal cliffs, raw material excavations) or excavations related to construction activities (buildings, bridges, harbours etc.) The results are described in field reports and published papers.
Recently, studies of fractures in clayey tills have been intensified. The reason for this is, that – in spite of the formerly assumption of the clayey till acting as a tight cover in relation to pollution – several investigations (Fig. 3 and 4) have shown that this is not the case (Gravesen & Rosenberg, 2009).

Figure 2. Excavation into clayey tills at Flakkebjerg, Sjælland (Photo: K.E.S.Klint).



a **b**

Figure 3. Clayey till sections 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).



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.4. Field localities where fractures in clayey till have been studied in excavations and cliffs. (From Klint in Gravesen & Rosenberg, 2009).

2.3 Field inspections

The potential areas will be visited during 2010:
Bornholm will be visited in May. Field inspections will be carried out at five areas identified from existing data.
Two areas on Falster and Lolland will also be visited during May.
Two localities on Sjælland will be visited in June.
In August seven areas in Jylland will be visited.
In October the Mol area in southern Belgian will be inspected, especially focusing on the fine grained Oligocene clays (Boom clay from Oligocene, Rupelian), which have

been chosen as a potential geological sediment for radioactive waste disposal (Wemaere et al., 2008).
Finally, in late autumn, three areas on Langeland and one area on Tåsinge will be visited and some of the areas in Jylland will be revisited.

2.4 Borehole data

2.4.1 Well data archive and Jupiter database.

The Well Data Archive at GEUS contains information on more than 300.000 shallow boreholes. Most of the boreholes are drilled in relation to ground water investigations and abstraction but boreholes related to raw material investigations, as well as geotechnical and scientific purposes are also stored in the archive. More than 240.000 of these boreholes are encoded into the JUPITER well database. The database includes administrative data, geological data and hydro geological data related to the wells, see Fig. 5 and 6 (Gravesen & Fredericia, 1984). Hydro chemical and physical borehole logs data are also available (Fig. 8). The database is assessable on www.geus.dk.
Sediment samples from the boreholes are geologically described and characterised at GEUS (Larsen et al., 1988).

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BORERAPPORT — **DGU arkivnr: 246. 805**

Borested : Aakirkebyvej 139
3700 Rønne

Kommune : Bornholm
Region : Hovedstaden

Boringsdato : 14/6 2000 — **Boringsdybde** : 12 meter — **Terrænkote** : 27 meter o. DNN

Brøndborer : United Drilling Contractors
MOB-nr :
BB-journr :
BB-bornr : 2-2000

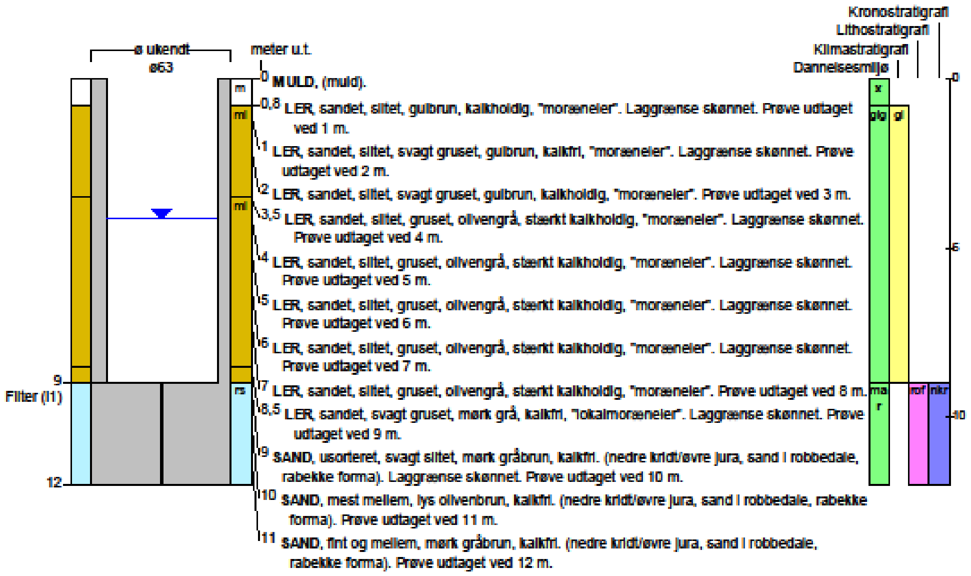
Prøver
- modtaget : 2/12 2002 **antal** : 12
- beskrevet : 10/12 2002 **af** : TC
- antal gemt : 0

Formål : Monitering/kontrol
Anvendelse : Monitering/kontrol
Boremetode :

Kortblad : 1812IIINV
UTM-zone : 33
UTM-koord. : 482903, 6105275

Datum : ED50
Koordinatkilde : Amt
Koordinatmetode : KMS digitale kort

	Ro-vandstand	Pejledato	Ydelse	Sænkning	Pumpetid
Indtag 1 (seneste)	4,13 meter u.t.	14/6 2000			



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

meter u.t.	
0 - 0,8	mangler
0,8 - 9	glacigen - glacial
9 - 12	marin - nedre kridt (robbedale formation)

Figure 5. Log for the borehole No. 246.805 from the Jupiter Database at GEUS.

De Nationale Geologiske Undersøgelser for Danmark og Grønland

Udskrevet 16/3 2010 Side 1

BORERAPPORT **DGU arkivnr: 242. 156**

Borested : Gedser centralskole bor nr. 1
4874 Gedser

Kommune : Guldborgsund
Region : Sjælland

Boringsdato : 1/9 1960 **Boringsdybde** : 44 meter **Terrænkote** : 5.6 meter o. DNN

Brøndborer : Viggo Mortensen, Frejlev
MOB-nr :
BB-journr :
BB-bornr :

Prøver
- modtaget :
- beskrevet : 16/1 1961 **af** : G
- antal gemt :

Formål : Undersøg./videnskab
Anvendelse :
Boremetode :

Kortblad : 1511IIISØ
UTM-zone : 32
UTM-koord. : 689460, 6053302

Datum : ED50
Koordinatkilde :
Koordinatmetode : Dig. på koor.bord

	Ro-vandstand	Pejledato	Ydelse	Sænkning	Pumpetid
Indtag 1 (seneste)	2.65 meter u.t.	14/10 1960	0.6 m³/t	0 meter	24 time(r)

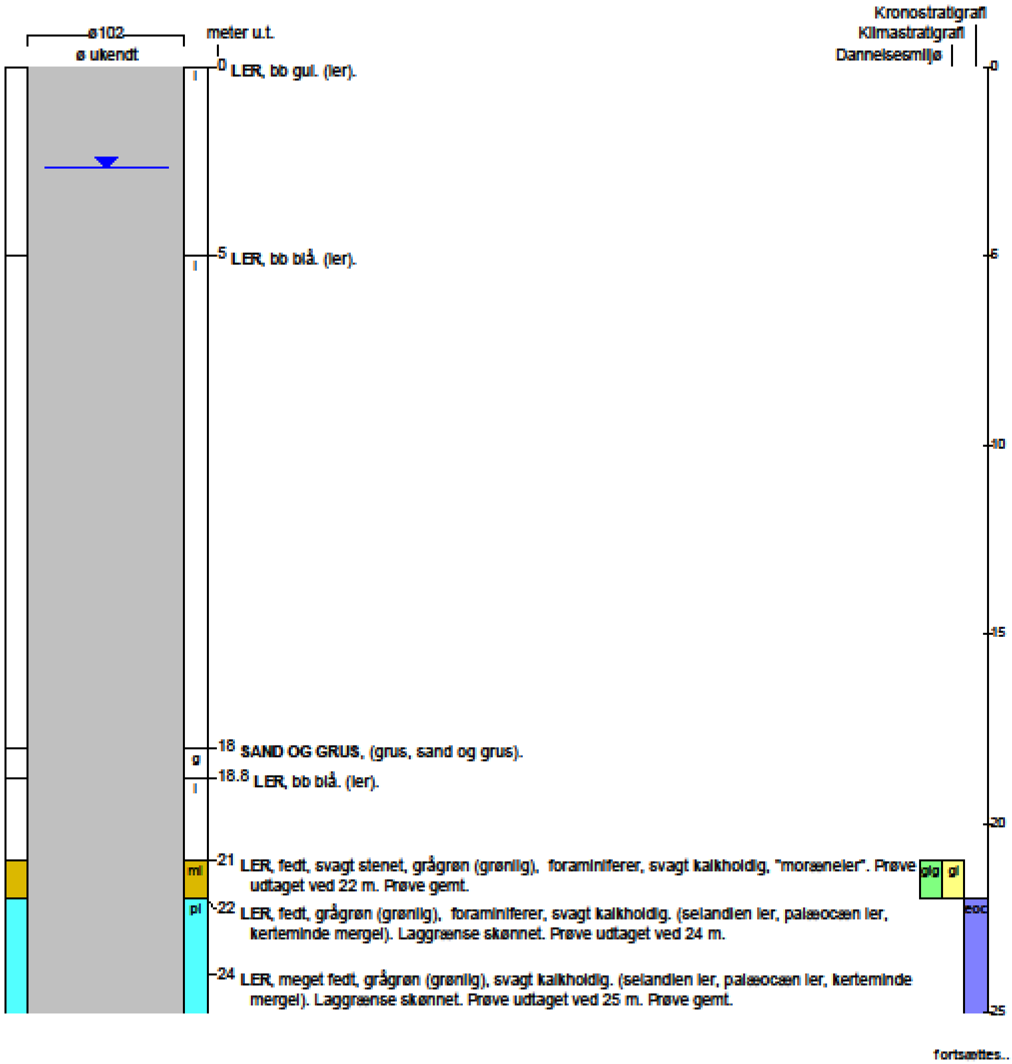


Figure 6. Log for the borehole No. 242.156 from the Jupiter Database at GEUS.

2.5 Shallow geophysical data

The Gerda geophysical database contains data from several types of geophysical investigations (Fig. 7): geo-electrical surveys (Wenner, Schlumberger, PACES, MEP), electromagnetic surveys (TEM, SkyTEM), borehole logs (Fig. 8) and seismic surveys. Data are assessable on www.geus.dk.

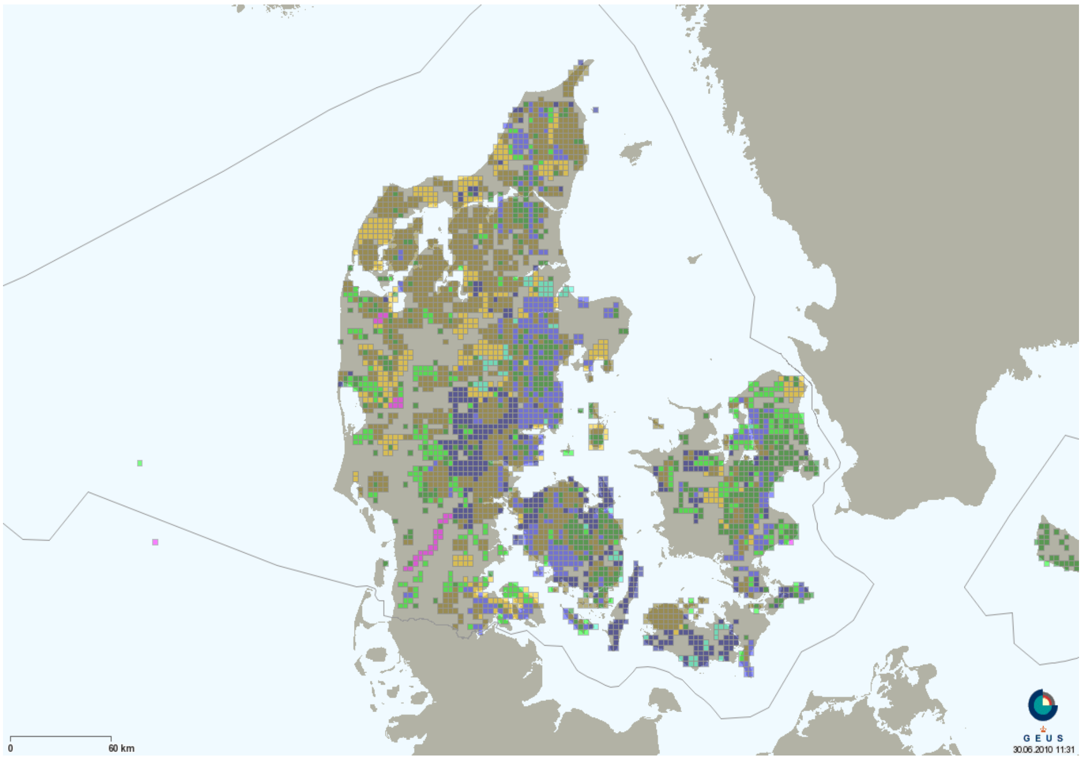


Figure 7. Interactive map, which can be used as entrance into the Gerda Geophysical database.
Legend: Green: MEP. Blue: Paces. Orange: SkyTEM. Dark blue: Schlumberger. Olive: TEM. Green blue: Wenner. Bordeaux red: Seismic.

Interpretations of the geophysical data can be found in reports in the report database (Rapportdatabase) on www.geus.dk (See later).

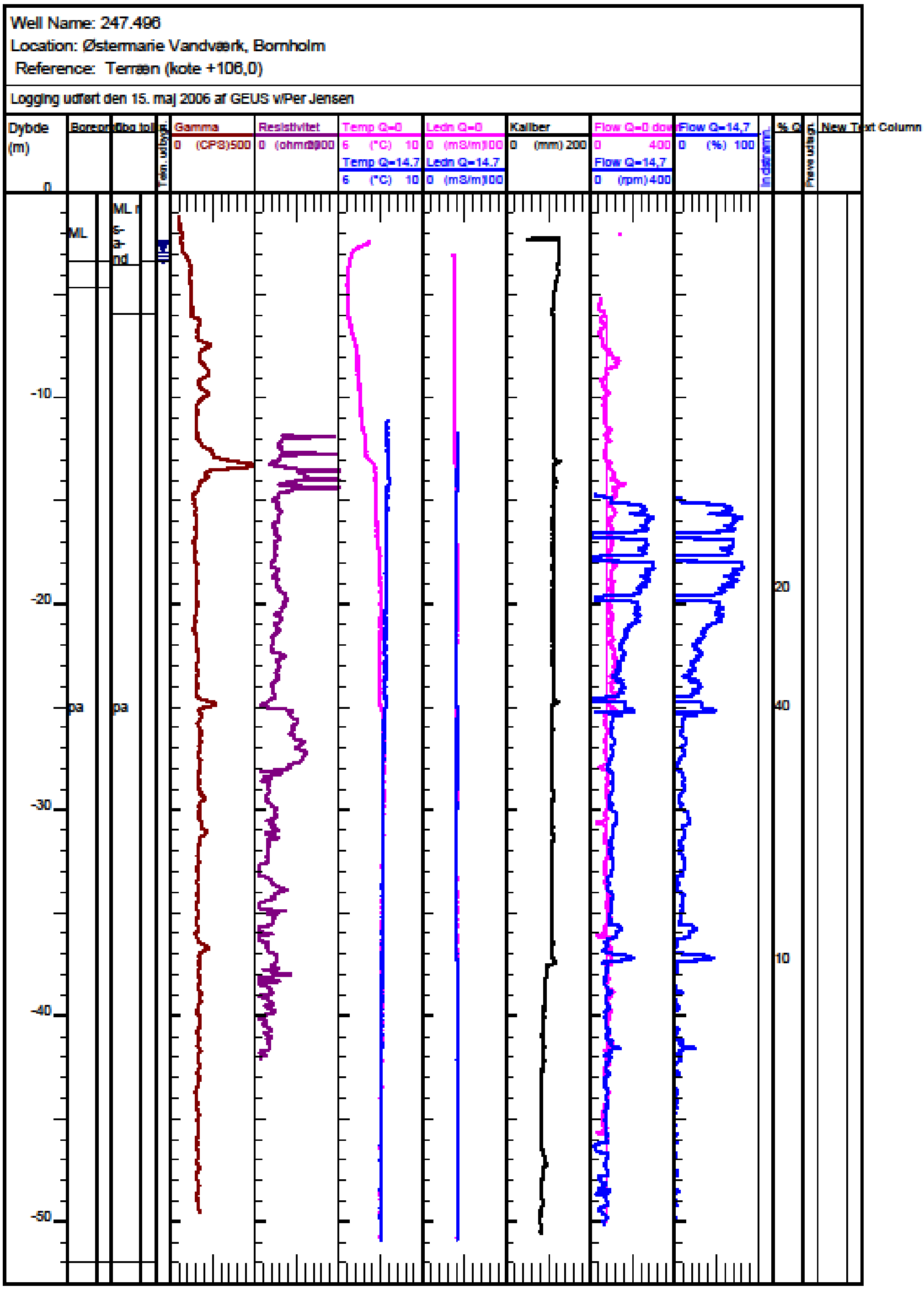


Figure 8. Physical logs from the borehole DGU No. 247.496. Legend: ML: Clayey till. Pa: Precambrian basement rocks.

2.6 Groundwater data

The Danish groundwater conditions have been monitored since 1990 primarily in the Danish Groundwater Monitoring Network (LOOP and GRUMO) as part of the National Action Plan Programme for Water Environment and Nature (NOVANA) (Stockmarr, 2005). The programme focuses on groundwater quality but the groundwater level is also measured in selected wells.

The quality monitoring is based on data from 1) approx. 6.200 public water supply wells, 2) 140 screens in a monitoring network of 70 catchment areas and 3) 100 shallow screens from five agricultural watersheds. The chemical analyses are stored in GEUS Jupiter database (Fig. 9).

Figure 9. Map showing the groundwater monitoring areas in Denmark. Legend: Green circles: GRUMO and LOOP areas. Red dots: melt water sand and gravel. White dots: Miocene/Oligocene sand. Yellow dots: Late glacial sand. Blue dots: Selandian limestone. Green dots: Danian limestone. Dark green dots: Maastrichtian chalk. Grey dots: Cambrian sandstone.

2.7 Rock and sediment mineralogy and chemistry

Abundant literature exists about the mineralogy and chemistry of Danish rocks and sediments.

2.7.1 Redox processes

Redox processes within the upper 2–3 meters of the uppermost geological layers (i.e. immediately below ground surface) cause oxidising, dilution and weathering processes. The yellow brown, non-calcareous clay deposits often have more macro pores and therefore a higher permeability than the calcareous grey till below. The map (Fig. 10) is based on borehole sediment sample information of colour changing from yellow, yellow brown and brown to grey. The redox interface is located between these layers.

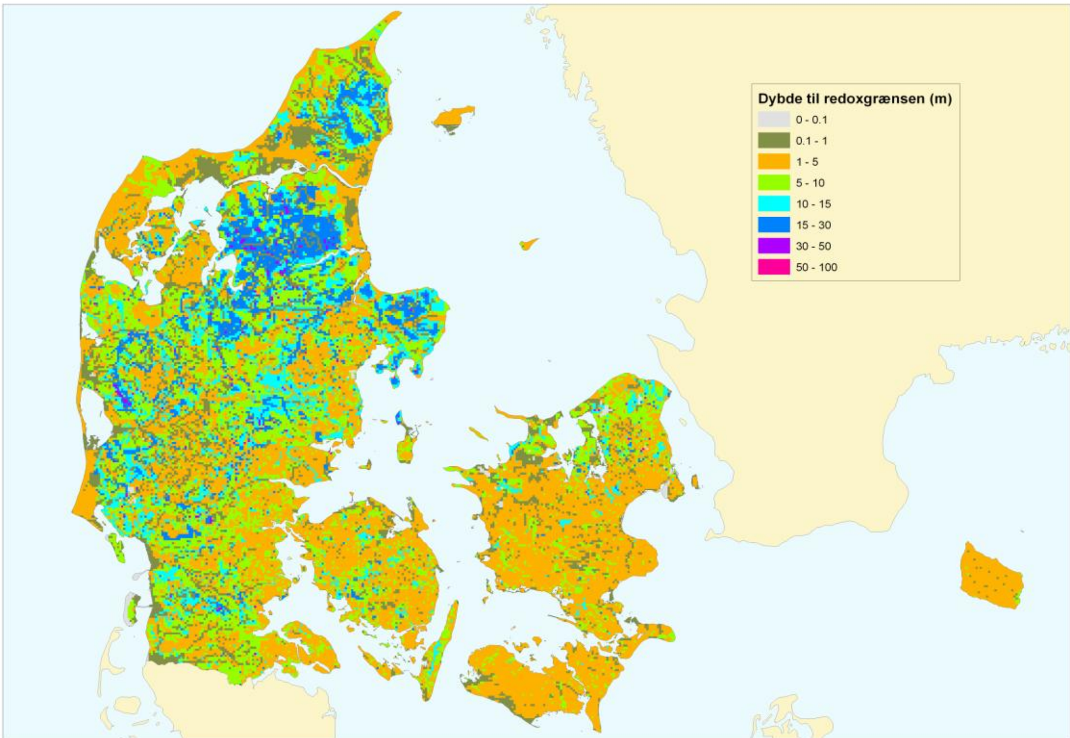


Figure 10. Digital map of the depth to the redox interface based on borehole data. Legend: The depth in meters. Grey is shallow and pink is deepest (Ernstsen et al., 2006).

2.7.2 Mineralogical and chemical composition of rocks and sediments

These data mainly occur in papers and reports but local databases at GEUS contain chemical data from surveys of raw materials and data of the content of radioactive components in the rocks and sediments.

2.8 Data from the National Groundwater mapping

Many geophysical, geological and hydrological data are collected along with the National Groundwater mapping. Most of these data are stored in the databases at GEUS.

2.8.1 Drinking water areas

As part of the Danish Government´s efforts to protect groundwater, the Environmental Centres in Denmark (former counties) 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.

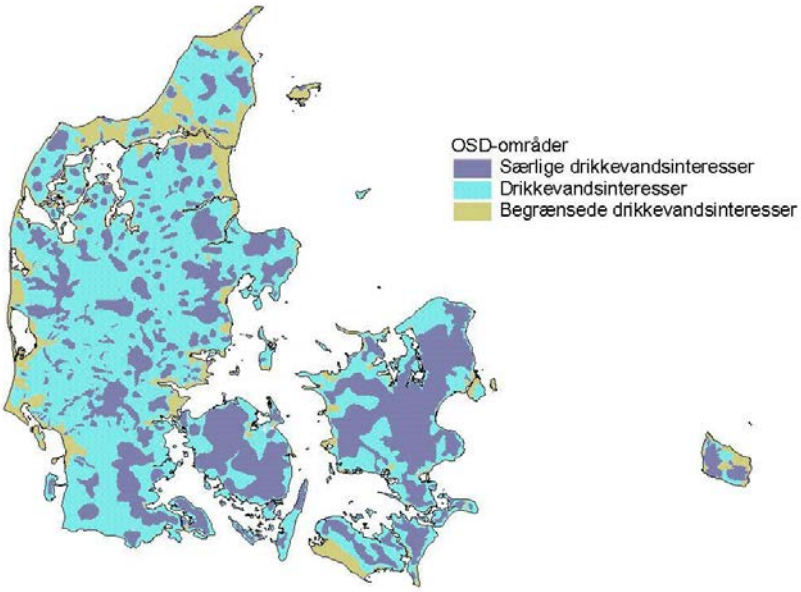


Figure 11. Digital map of the drinking water recharge areas in Denmark (OSD and OD areas). Legend: Purple: Areas of special drinking water interests (OSD). Light blue: Areas with drinking water interests (OD). Olive: Areas with limited drinking water interests.

2.8.2 Groundwater mapping

The seven Environmental Centres (Miljøcentre) belonging under the Danish Ministry of the Environment are responsible for the mapping of groundwater conditions within the OSD and OD areas. The mapping is carried out in co-operation with GEUS and several private consultant companies (Mielby, 2009). The mapping has to be finished in 2015.

All data, maps and reports are delivered to GEUS who store this in archives and databases.

Examples of the progress in the work and investigations are demonstrated for three Environmental Centers: Miljøcenter Nykøbing Falster (Fig. 12), Miljøcenter Roskilde (Fig. 13) and Miljøcenter Odense (Fig. 14).

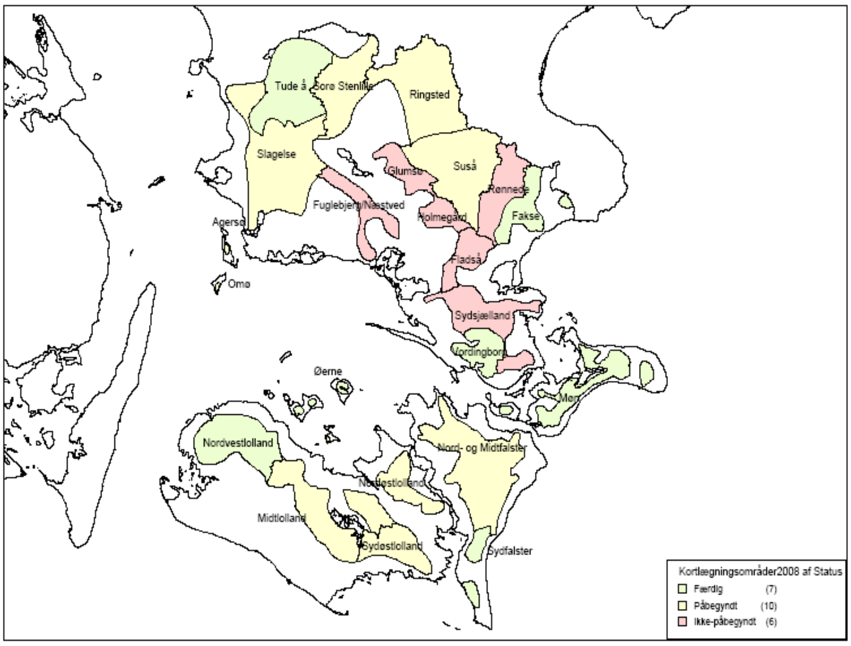


Figure.12. Map of the groundwater areas that Miljøcenter Nykøbing F. has mapped and is going to map the coming years. Legend: Green: finished areas. Yellow: work in progress. Red: not started yet.

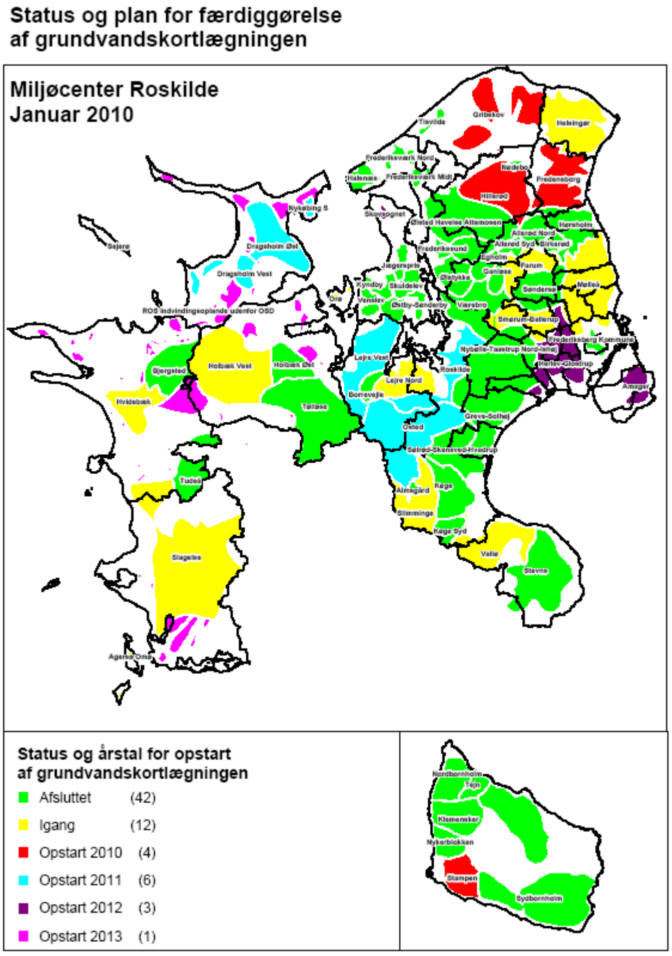


Figure 13. Map of the groundwater areas, which Miljøcenter Roskilde has mapped and is going to map the coming years. Legend: Green: finished. Yellow: work in progress. Red: started in 2010. Blue, purple and pink: not started yet.

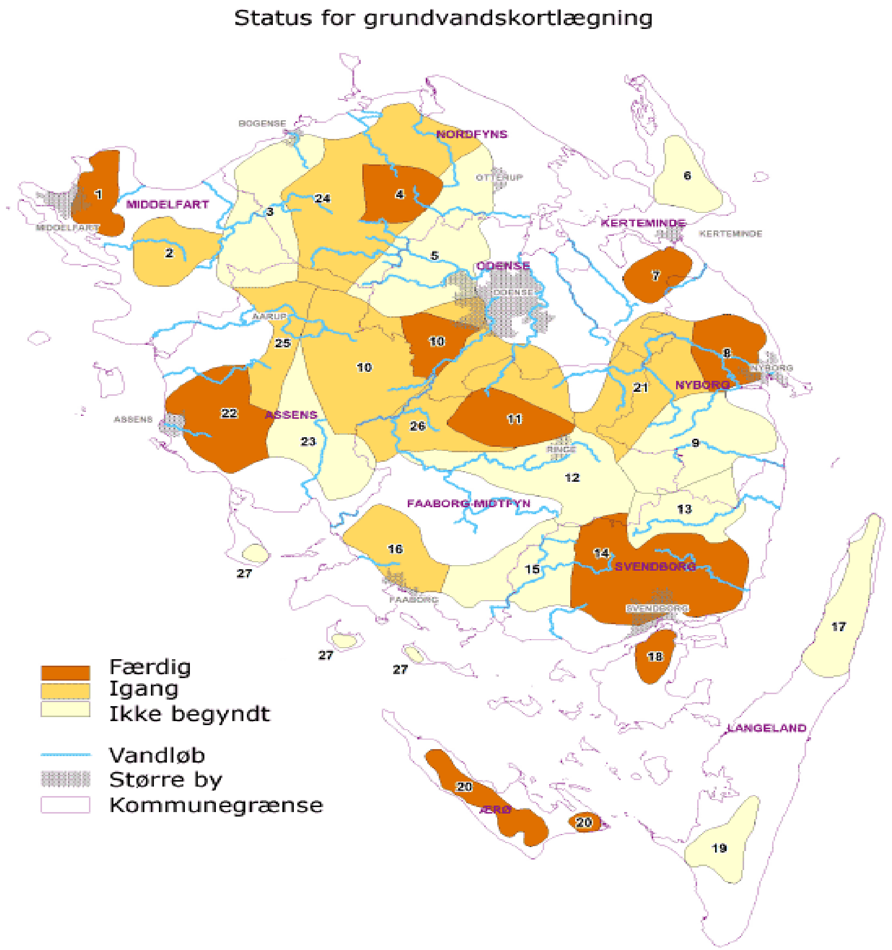


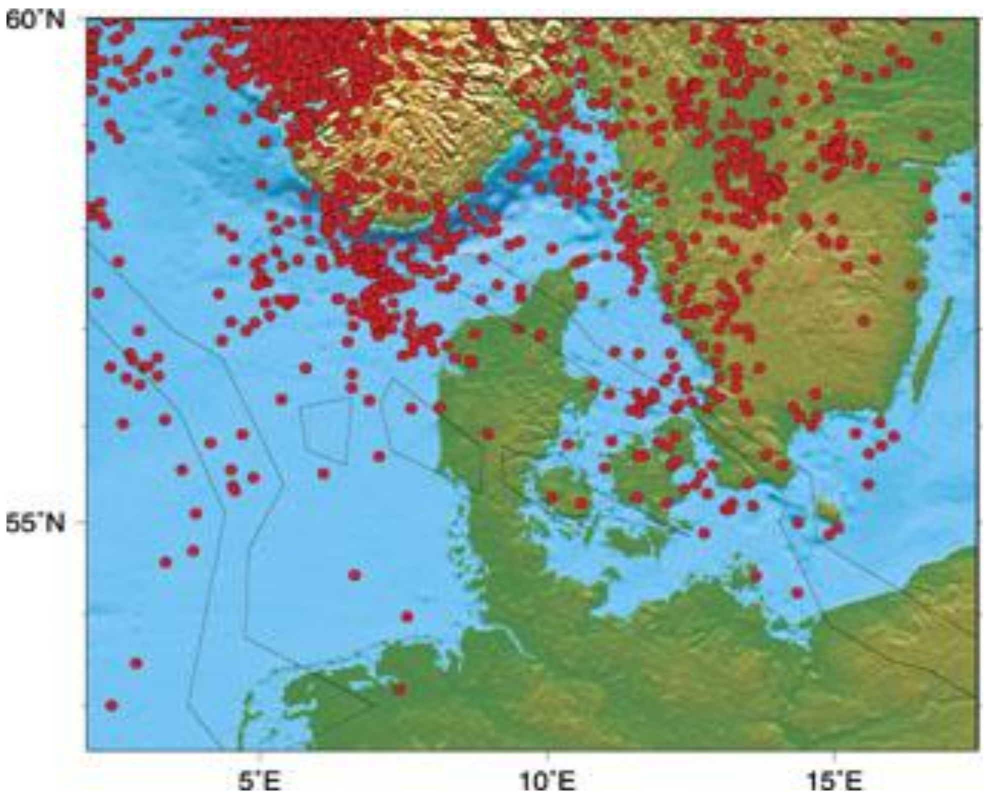
Figure 14. Map of the groundwater areas that Miljøcenter Odense has mapped and is going to map the coming years. Legend: Yellow brown: finished. Yellow: work in progress. Light yellow: not started yet.

Similar plans have been developed for the remaining Environmental Centres (Miljøcenter Ribe, Miljøcenter Århus, Miljøcenter Viborg and Miljøcenter Aalborg).

2.9 Earth quake data

Earth quake data are collected from five Danish stations: Bornholm, Vestvolden in København, Gilleleje, Stevns and Mønsted. The stations register seismic disturbances in the subsurface. These data are combined with the same type of data from neighbouring countries (Fig. 15). Data are stored at GEUS. Historical data concerning earth quakes are described in the literature (e.g. see Abrahamsen, 1967, Bondesen, 2001).

a.



b.

Figure 15. a. Location of the five Danish seismic stations. b. Map showing the epicentres of earth quakes in Danish areas and the surroundings. (From GEUS homepage: www.geus.dk).

3. MAPS

3.1 Quaternary Maps in scale 1:50.000 and 1:100.000

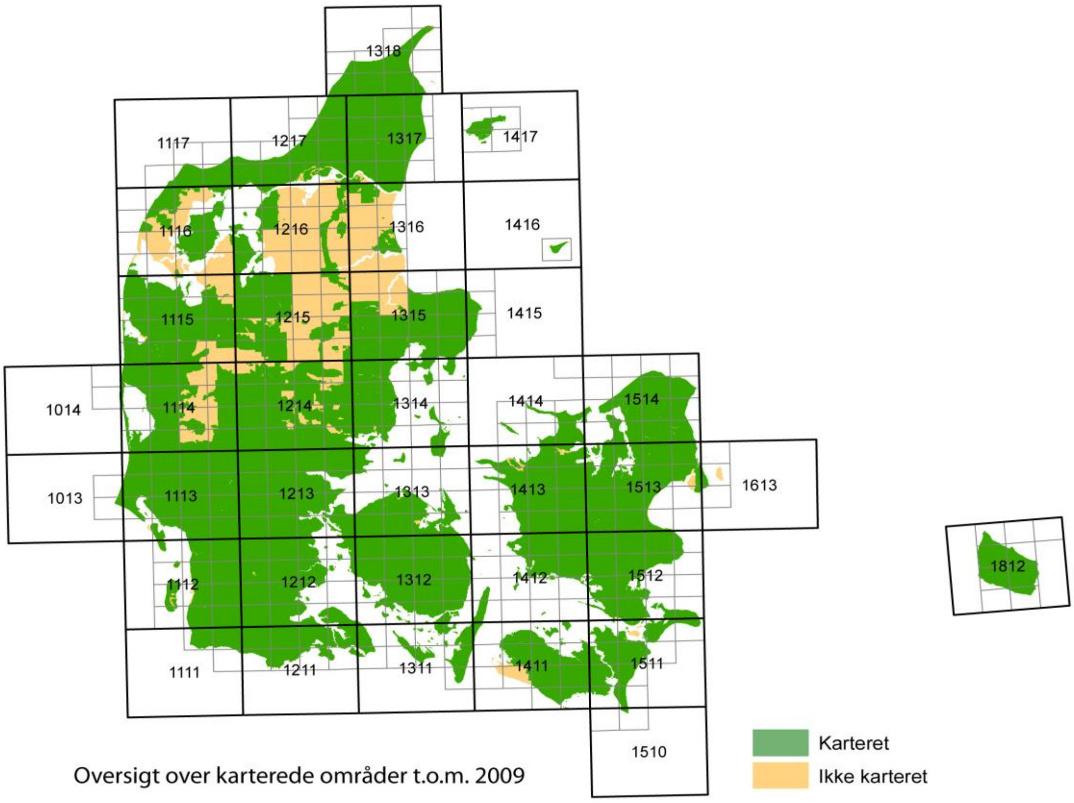


Figure16. Status for the mapping of the Quaternary surface deposits in scale 1:50.000 (1:100.000). Legend: Green: mapped. Yellow: Not mapped. (Mielby, 2009).

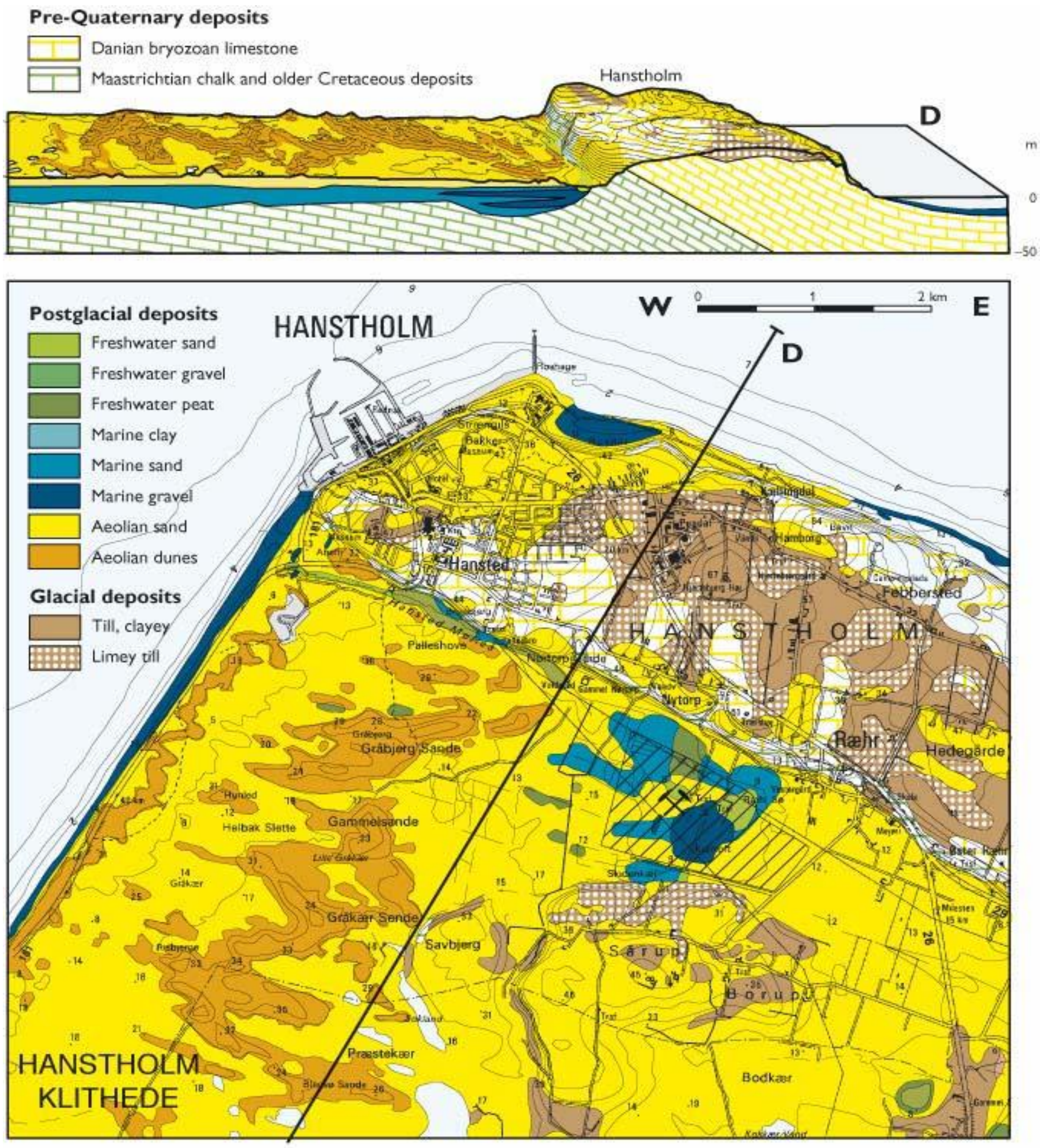


Figure 17. Map of the Quaternary surface deposits. Part of the map sheet Hanstholm. Original scale 1:50.000. (From Pedersen & Petersen, 2003).

The mapping of Denmark started in 1888 but 14 % of the area still remains to be mapped (Gravesen et al, 2008). The maps show the surface geology in the depth of 1 meter below terrain. The mapping is carried out in the field using an auger by which a sediment sample is taken every 200 meters apart. The maps are produced in the field where boundaries between different units are drawn. The map is an interpretation of the geology in the mapped area. Therefore, all information in the area is included. The maps are printed in scale 1:50.000 (Fig. 17) but are also stored in a digital form. Status for the mapping is shown in Fig. 16.

3.2 Quaternary Maps in scale 1:200.000

The Quaternary maps in scale 1:200.000 are compiled from the maps in scale 1:50.000 (1:25.000). The map (covering all Denmark) is produced as four printed map sheets and is also found as a digital product. Figure 1 shows the map of the Quaternary surface deposits.

3.3 Geomorphologic maps

Several geomorphologic maps have been produced during time (Hansen & Milthers, 1954, Smed, 1979, 1981, 1982) but recently, a series of new maps is prepared in scale 1:200.000 (Fig. 18).

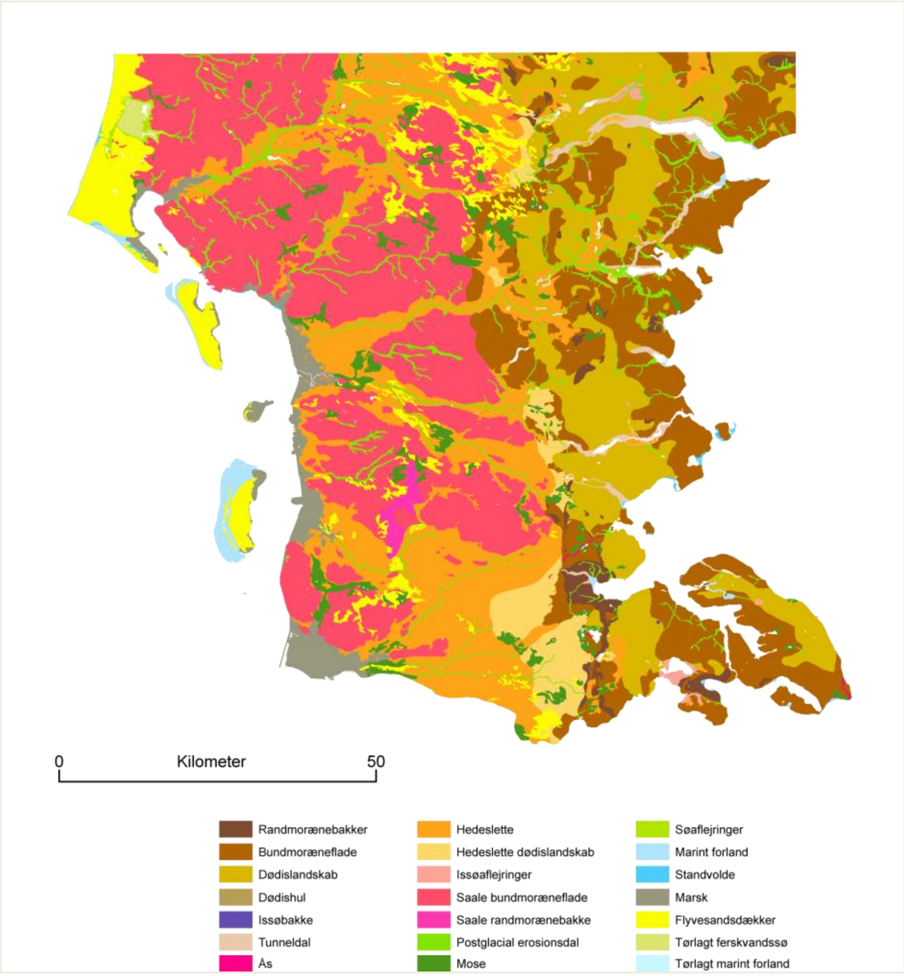


Figure 18. Map of the geomorphologic units, Southern Jylland. Original scale 1:200.000. Legend: East Jylland with brown colours: clayey and sandy till landscapes. West Jylland with red and yellow colours: sandy and gravely sandurs and hilly islands covered by some Holocene coastal deposits (Jakobsen in Gravesen et al., 2006).

3.4 Poly-morphologic maps

The poly-morphologic maps are compiled and interpreted by combining the geomorphologic maps, the Quaternary surface maps and information from boreholes. The maps demonstrate the relationship between surface processes and deposits and the underlying deposits, which are classified into new units (Fig. 19).

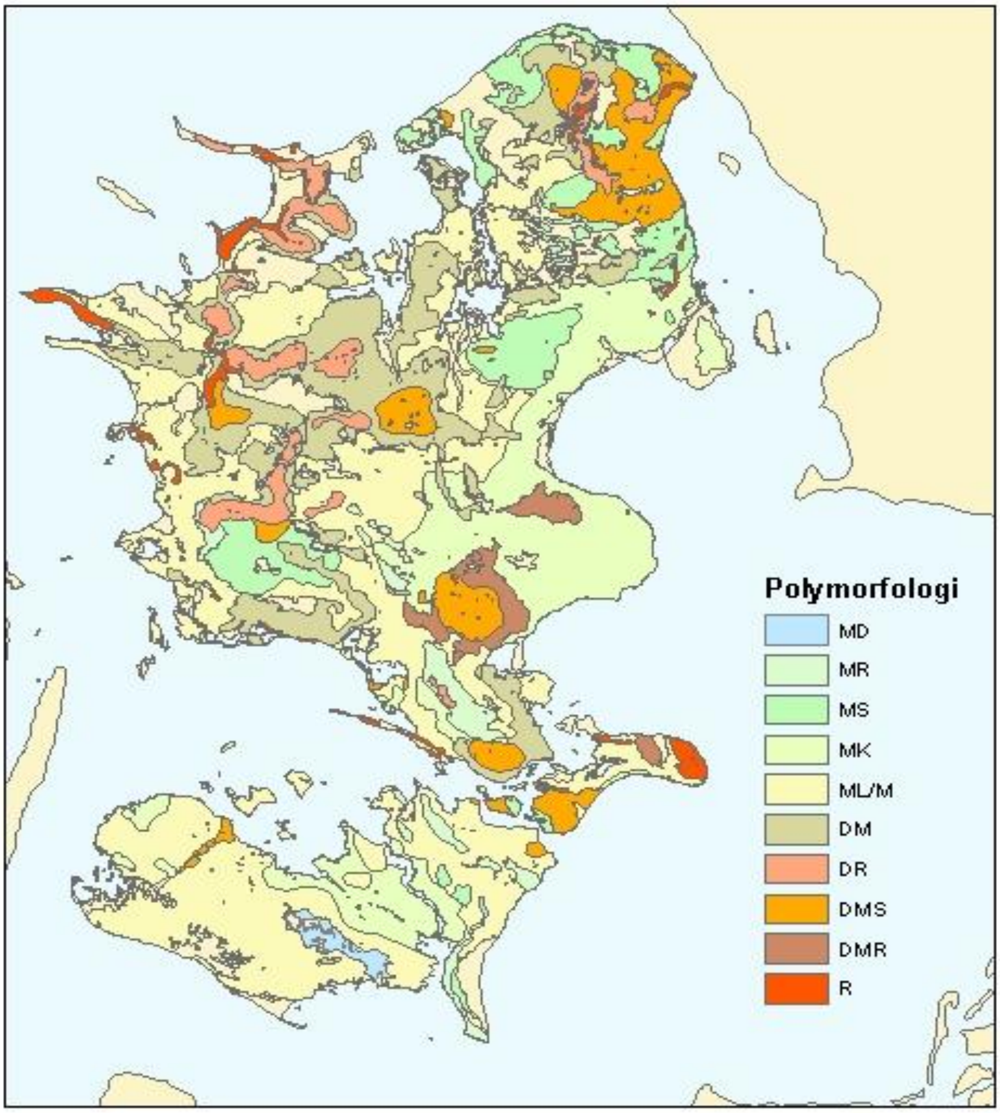


Figure 19. Digital map of the poly-geomorphologic units in the eastern part of Denmark. Legend: Examples: MS: moraine plain above melt water plain. MK: moraine plain above chalk and limestone deposits. DR: border push up moraine deposits (Klint in Gravesen & Rosenberg, 2009).

3.5 Topographic maps

The topographic maps from the National Survey and Cadastre (KMS) are important tools. The digital product Top10DK is the basic map type but also older map sheets found at the KMS homepage (www.kms.dk) are relevant for the evaluation of the development of the landscape.

3.6 Maps of the pre-Quaternary surface

Two types of maps of the pre-Quaternary surface are relevant: The map of the level of the surface and the map of the distribution of the deposits and rocks (and age) at the surface. A third map shows the thickness of the Quaternary deposits above the pre-Quaternary surface.

3.6.1 Map of the level of the pre-Quaternary surface

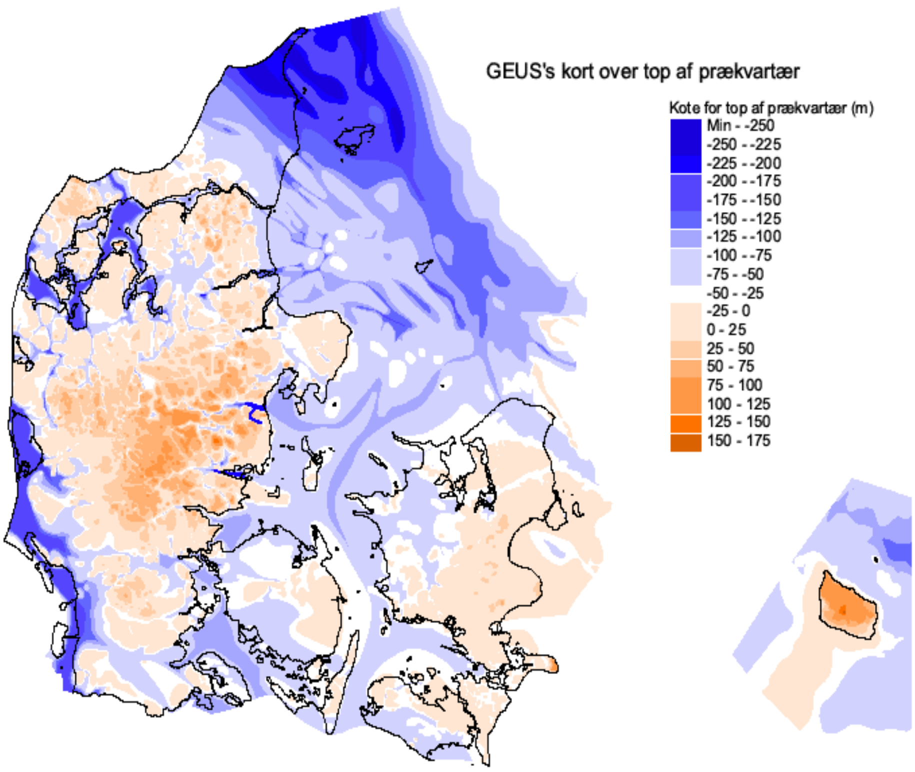


Figure 20. Map showing the level of the pre-Quaternary surface. Original Scale 1:500.000. Legend: Level of the top of the surface in meters. Blue is deepest and red is highest (From Binzer & Stockmarr, 1994).

The map is based on information from boreholes supplemented by additional information from seismic surveys (Fig. 20).

3.6.2 Map of time units and formations on the pre-Quaternary surface

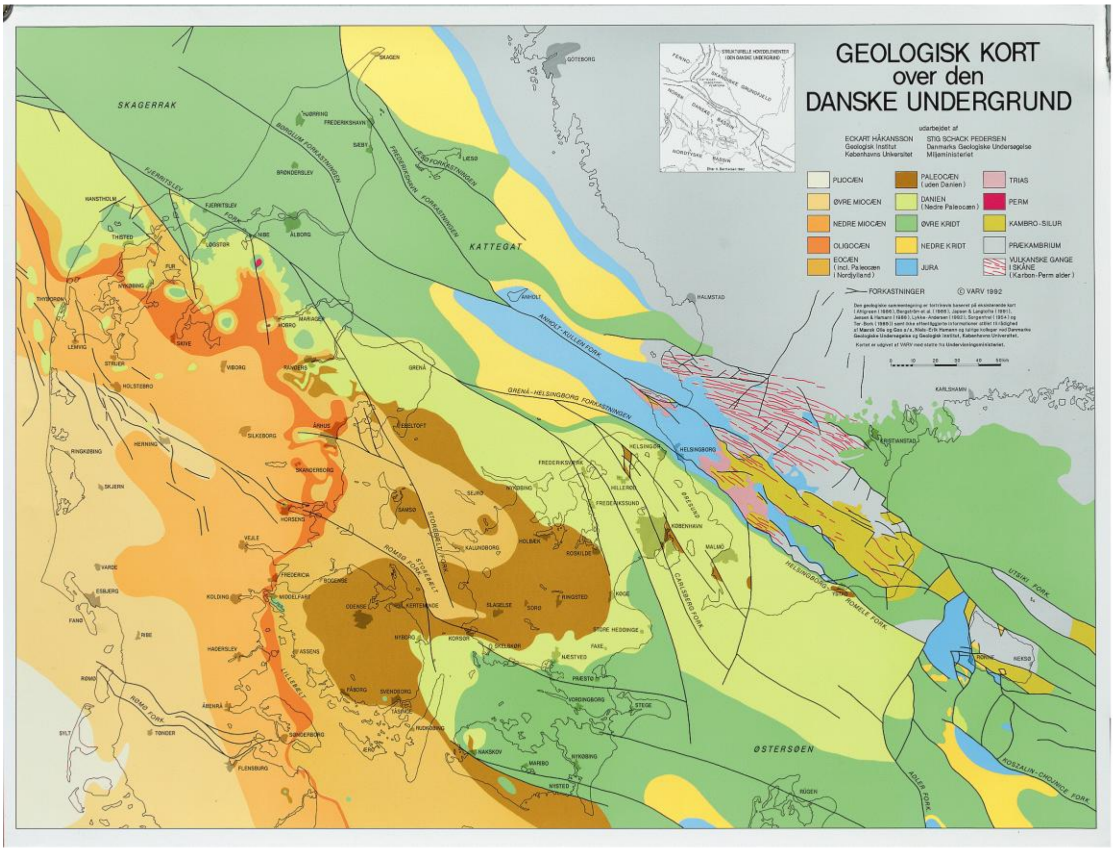


Figure 21. Map of the pre-Quaternary surface: Time units. Original scale: 1:50.000. Legend: Red lines: Precambrian intrusions. Grey: Precambrian. Olive: Cambrian-Silurian: Red: Permian. Light red: Triassic. Blue: Jurassic. Yellow: Lower Cretaceous. Green: Upper Cretaceous. Light green: Danian. Brown: Paleocene. Yellow olive: Eocene. Red brown: Oligocene. Light yellow brown: Lower Miocene. Very light yellow brown: Upper Miocene. White: Pliocene (Håkansson & Pedersen, 1992).

The map is produced on knowledge from boreholes, outcrops, seismic data and geological literature (Fig. 21).

3.6.3 Map of the thickness of the Quaternary deposits.

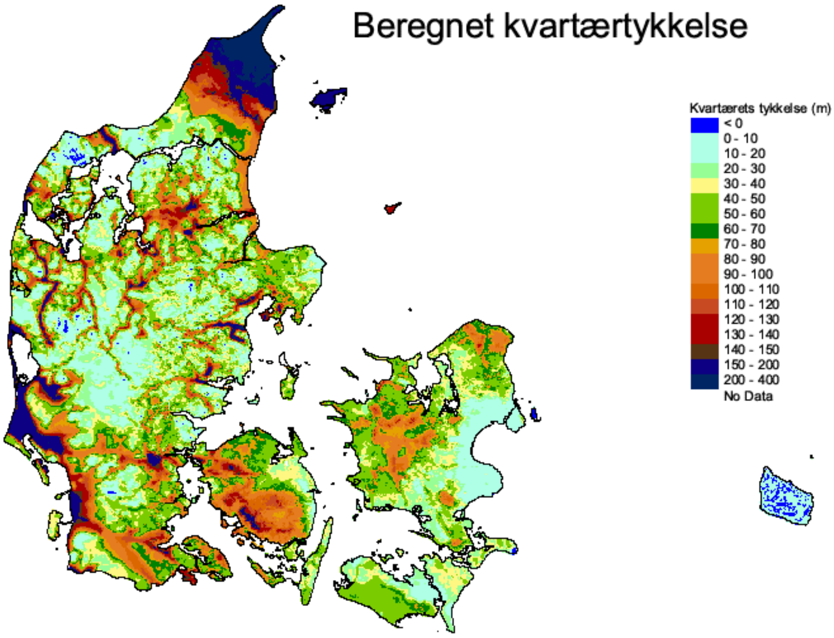


Figure 22. Map of the thickness of the Quaternary deposits. Original scale: 1: 500.000. Legend: Thickness of the Quaternary deposits in meters. Dark blue is thickest and bright blue is thinnest (Frants v. Platen, GEUS).

The map of the thickness of the Quaternary deposits is constructed from borehole data in the Jupiter database. By means of GIS manipulation and the code system of the different layers in the database, it is possible to produce this map (Fig. 22).

3.7 Mapping of buried valleys

The map of the buried valleys (Fig. 23) is produced from knowledge of the position of the valleys in the geological surface layers. The mapping of the valleys is mainly based on seismic data but other kinds of geophysical data are incorporated as well. Borehole data are used to confirm the age and lithology of the mapped units. (Jørgensen, & Sandersen, 2009)
The mapping results are found on www.begravededale.dk.

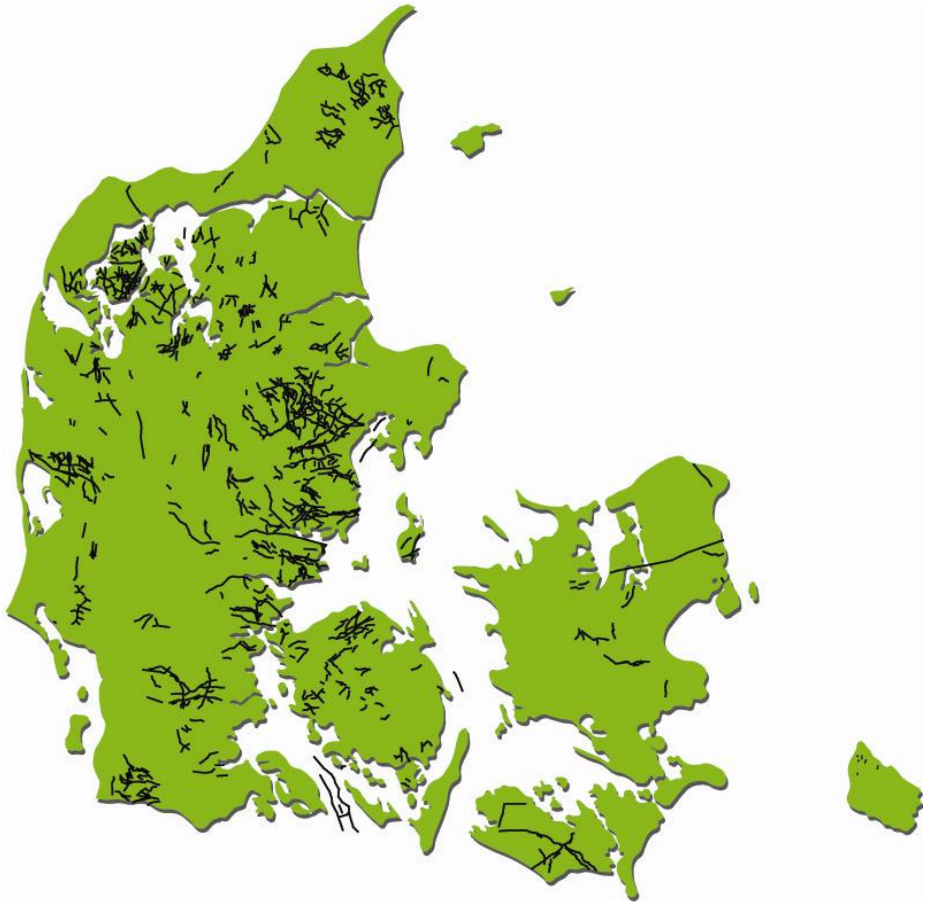


Figure 23. Distribution of buried valleys in Denmark. The map includes all valleys known in 2009 (Jørgensen & Sandersen, 2009).

3.8 Hydro geological mapping of Denmark

3.8.1 Geological Basic Data maps

Geological Basic Data Maps in scale 1:50.000 are based on borehole data from the Well Data Archive at GEUS. The maps show the geological data in the form of circles, so-called Cyclograms (Fig. 24). The method is described in Andersen & Gravesen (1989). DGU/GEUS produced approximately 70 maps during the period 1978 – 1990. Information about the geological layers is presented by means of letter symbols and colours in the Cyclograms. Most of this information comes from geological characterization and description of sediment and rock samples from the boreholes but also interpretation of the geological layers *without sample description* was important. A lot of hydro geological information is also attached to the circles. In some part of the country only circle maps without geological interpretation of the layers were produced.

Figure 24. Geological Basic Data map. Example from the south western part of Bornholm. Original Scale: 1:50.000. Legend: see Gravesen & Rasmussen, 1988.

These maps are the most important information in relation to understanding the regional and local evolution of the geological conditions.

3.8.2 Chemical Basic data Maps

The Chemical Basic Data Maps in scale 100.000 show the major ions in the groundwater. Data are presented in pie charts. The chemical analyses show the groundwater composition that is measured in the boreholes.

3.8.3 Transmissivity and ground water level maps

These maps in scale 100.000 show the transmissivity in the most important reservoirs in Denmark: Quaternary sand and gravel, Tertiary sand and Paleocene and Cretaceous limestone and chalk. Also the level of the groundwater surface is shown besides with the groundwater divides and the groundwater recharge areas.

3.8.4 Maps of the pre-Quaternary surface

The pre-Quaternary maps in scale 100.000 show the sediments at the surface: type and age, and the level of the surface. These maps were constructed with respect to the hydro geological conditions and the need for information about the groundwater reservoirs.

3.9 Raw material mapping

The raw material mapping started locally in the counties 1979-1980 by compiling of a series of different maps, such as: locality map (of the pits and quarries), borehole maps, geomorphology maps, surface geology maps and finally, the conclusive raw material maps. Afterwards detailed investigations in smaller selected areas were carried out. An abundant amount of reports and maps are available.

3.10 The New National Groundwater Mapping

The new groundwater mapping generates several types of output maps: geophysical maps with interpretations, special geological maps, groundwater resource maps and water quality maps (Mielby, 2009).

4. GEOLOGICAL MODELS

4.1 Analogue models

Geological models have always been constructed aiming to illustrate the more or less complex geological conditions. 2D and 3D models can been found in the literature and reports often as bloc diagrams (Fig. 25). In connection with groundwater modelling these models have been digitized and used as the framework in the groundwater models (Klint & Gravesen 1999).

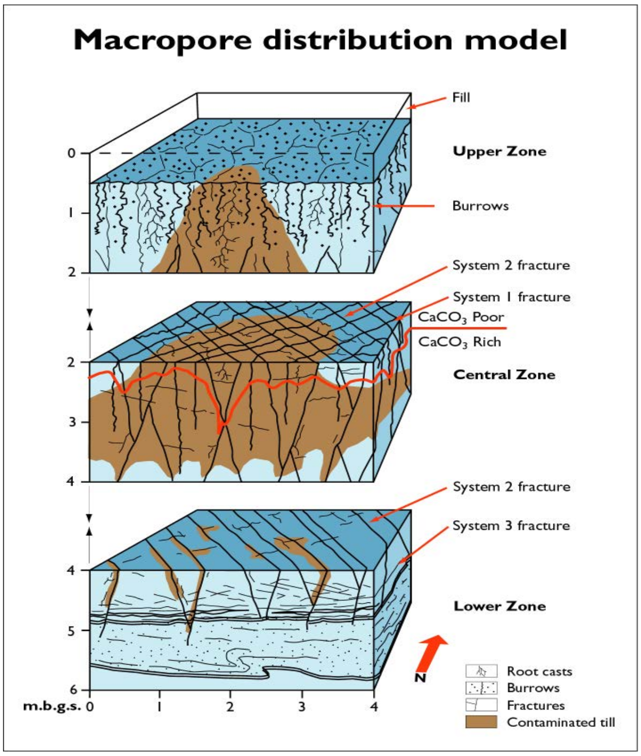


Figure 25. 3-D Model for the upper 6 meters in Flakkebjerg, Denmark. The model illustrates the fracture and macro pore framework and $CaCO_3$ distribution in clayey till. (After Klint & Gravesen, 1999).

4.2 Digital models

The most simple 2-D geological model is a digital cross section constructed from borehole data (Fig.26).

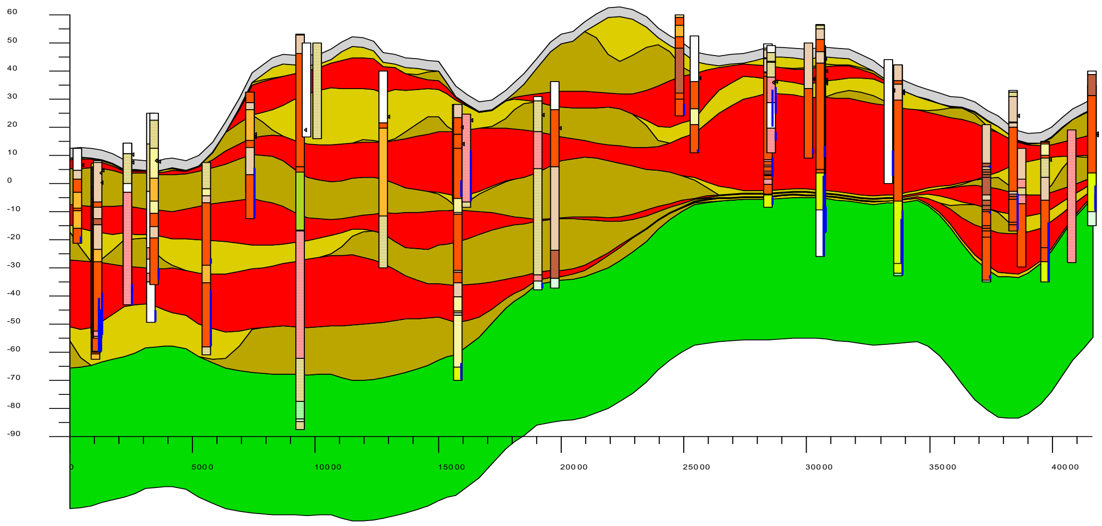


Figure 26. Geological section (2D model) from the National Groundwater Model (Danmarksmodellen).

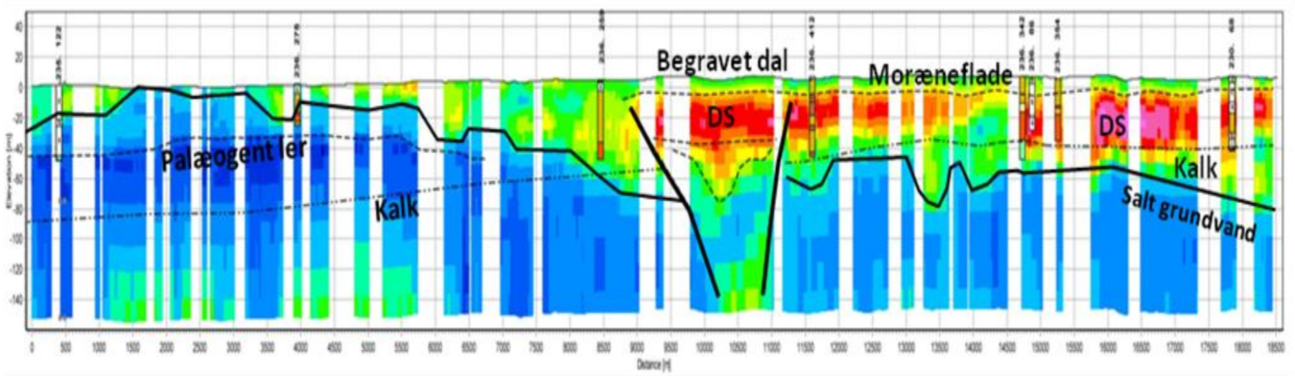


Figure 27. Geological section from central Lolland, showing a combination of data from the geophysical SkyTEM model and borehole data, resulting in a detailed 2-D model along the section (Jørgensen in Mielby, 2009).

Combinations of interpreted geophysical measurements and borehole data can give a much more detailed 2-D model (Fig. 27).

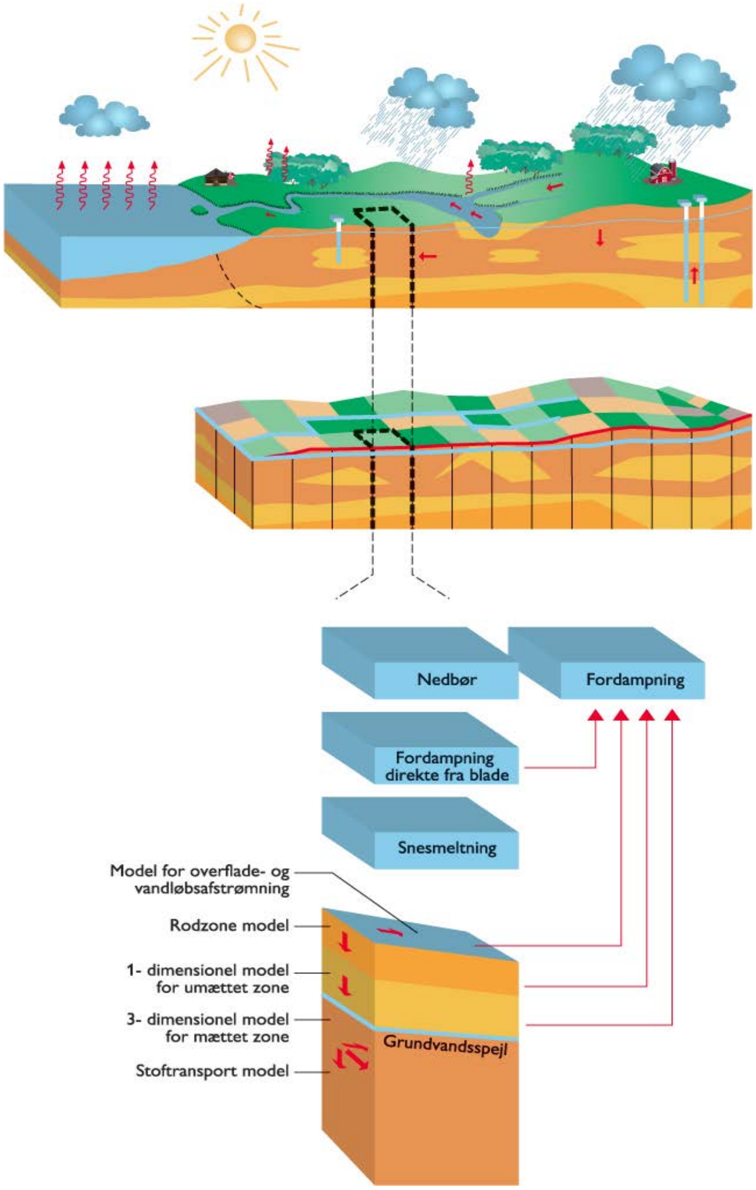


Figure 28. 3-D models can be constructed based on detailed geophysical surveys and many boreholes.

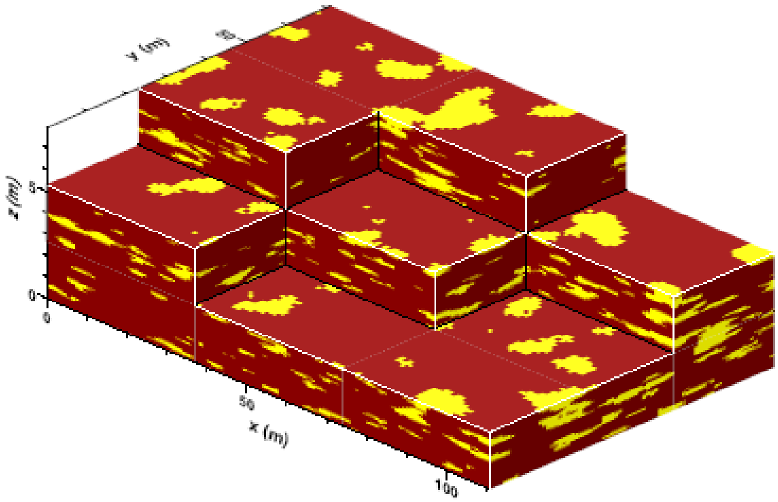


Figure 29. Digital geo-statistic model of the distribution of sand lenses in clayey till (from Pedersen, 2004).

The construction of 3-D geological models is especially useful for the modeling of the groundwater conditions in relation to the formation and flow of the groundwater, and to the transport of the groundwater components as well (Fig. 28 and 29).

4.3 Model database

Digital geological models are stored in the model database at GEUS (www.geus.dk). The models are primarily produced in connection with the National Groundwater mapping, but other models are/will be included in the database as well.

4.4 Terrain conditions - terrain models

The digital terrain model (Fig. 30) is based on data from KMS (www.kms.dk). It is very valuably in relation to description and evaluation of the terrain, not least concerning the processes of landscape development and the recent variation of the landscape (Dala & Knudsen, 2009).

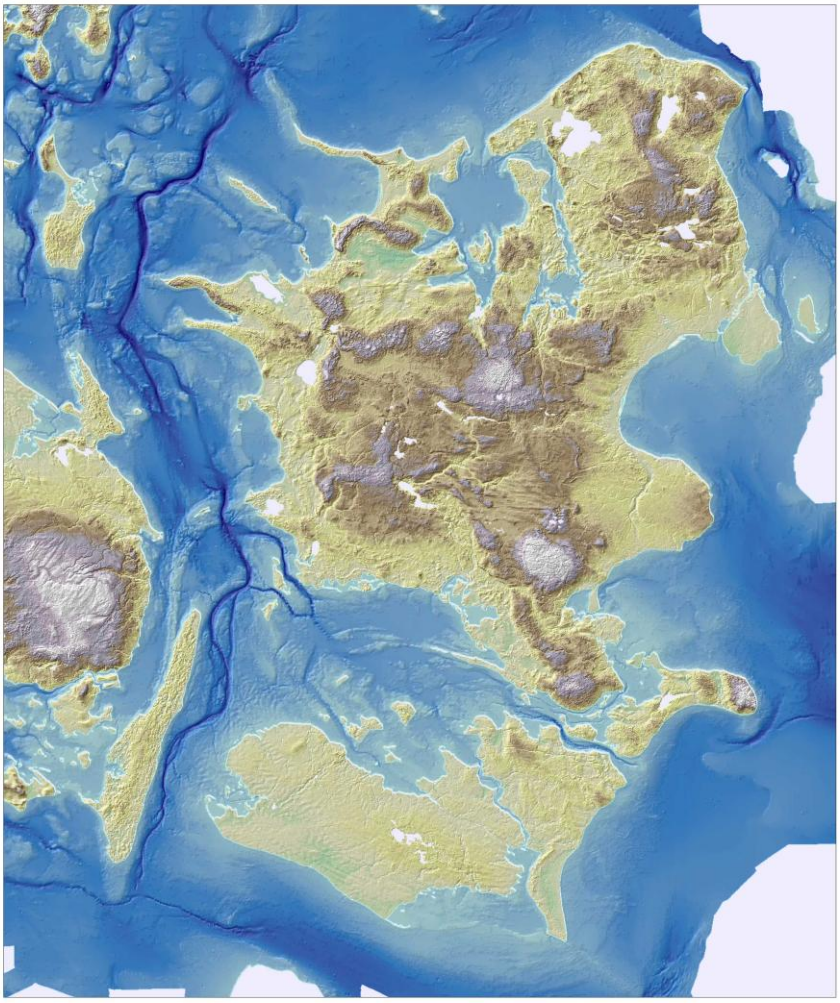


Figure 30. Digital terrain model for eastern Denmark. (F. v. Platen, GEUS).

5. Reports, publications and important information

5.1 Reports and publications

An abundant literature on Danish geology and hydrogeology with details on groundwater quality and quantity exists in printed publications, reports and maps.

5.2 Report database

The report database at GEUS contains many reports produced in connection with hydro geological and raw material investigations in Denmark. The Database is open for the public (www.geus.dk).

5.3 NATURA 2000 and protected areas

Information on Natura 2000 areas and protected areas are hold by the Agency for Spatial and Environmental Planning (By- og Landskabsstyrelsen, BLST) and most of the data are found on home page www.blst.dk.

5.4 Infrastructure, sea and land area

Infrastructure maps are found on homepage of the National Survey and Cadastre (Kort- og Matrikelstyrelsen, KMS) www.kms.dk. Calculation on the sea level rise and relation to isostatic land rise is found in Knudsen & Vognsen (2010).

5.5 Information of climate and climate changes

Information on the recent and future climate and the forecast scenarios is hold by Danish Meteorological Institute (Dansk Meteorologisk Institut, DMI). Different calculations of the future scenarios are published in small reports on the home page www.dmi.dk. and on the homepage www.klimatilpasning.dk (from the centre of "Climate Change Adaption" under the Ministry of Climate and Energy).

6. Methods

The characteristics of *and* demands for a potential site for low- and intermediate radioactive waste (LLW and ILW) are described in Indenrigs- og Sundhedsministeriet (2007). These guidelines are based on the recommendations in IAEA reports (1994, 1999, 2005). The first step to find a suitable waste disposal locality is to recognize approximately 20 larger areas from which it is possible to choose 1-3 localities for detailed investigations. The first selection is based on interpretation of existing data.
This chapter describes the methods used in the selection of the app. 20 sites.

6.1 General reports

A detailed description of the data types that are needed for a selection and evaluation of approximately 20 potential disposal areas is presented in the report (Indenrigs- og Sundhedsministeriet, 2007). The chosen data and information follow the guidelines from the work of IAEA (1994, 1999, and 2005), which are generally accepted in all countries. The considerations of the Atomenergikommissionen (1976) and Dinesen et al. (1977) have also been used as background information.
The disposal has to be near-surface: On the ground surface, down to 30 meters below ground surface or between 30 and 100 meters below the ground surface. Near-surface disposals are known from United Kingdom in Cumbria, Spain at El Cabril, France, Japan and USA. Near-surface caverns in basement rocks are known from Sweden at Forsmark and in Finland (see e.g. SKB, 2007 and Finnish Energy Industries, 2007). Fine-grained Tertiary clay may be used in Belgium for a geological disposal (www.wold-nuclear.org).

6.2 Area/Site specifications

The concept, based on the guidelines mentioned above, will be used in the evaluation of each area, site or locality. The evaluation and use of the concept has to include the total succession of strata from the ground surface down to at least 100 meters below ground surface.
The concept is build up and based on several different kind of information, which have to give a picture of the best possible natural conditions at a site for the waste disposal:

a. Geological conditions
a1. General geology
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. Hydro geological conditions
b1. Drinking water areas
b2. Groundwater characteristics
b3. Reservoir and cover sediments and rocks
b4. Geo- and hydro chemical 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

These chapters have to address the following important items:

1. The disposal should be situated in an area with homogeneous geological conditions. It should be demonstrated that these conditions – to a high degree of probability – are fulfilled at the selected sites. The geology of Denmark is relatively heterogeneous in most areas. Still, it is the goal to find continuous and homogeneous sediment or rock layers.
2. The geological deposits shall contribute to the isolation of the radioactive waste. This is most effectively met if the disposal is underlain and/or surrounded by tight layers such as e.g. clays, silts, limestone or basement rocks.
3. To restrict the water flow away from the disposal it will be appropriate, if the disposal is sited in low permeable deposits.
4. The disposal shall be placed at the longest possible distance from the nearest ground water aquifer. The surrounding deposits or rocks shall have low streaming conditions.
5 The disposal shall be located outside areas of special recharge ground water and drinking water interests (OSD areas).
6. The ground water conditions shall contribute to dilution of radioactive components that have left the disposal.
7. The sediments, rocks and ground water shall promote sorption of leaking radioactive components.

8. Geological processes on the ground surface may not be able to influence on the security of the disposal.

6.3 The first screening of the areas based on geological information

The first screenings of the approx. 20 areas will be accomplished at meetings with geological expertise at GEUS. Scientists with different expertise background will discuss the possibilities and a gross list of potential areas will be established. During the same part of the process, the potential sediments and rocks will be evaluated and described (Report no. 2).

During an evaluation of the sediment and rocks 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 will be excluded from a list of potential disposal sites.
Following this procedure, 40 % of the land area will not be evaluated any further.

6.4 Field inspections

At first, the areas will be described primarily based on existing data and without any kind of field work. Secondly, after this first compilation of the data, the evaluation of the potential areas will be supplemented by an inspection of the conditions in the field. Amongst other things, a photo documentation of each area is to be collected.

6.5 Evaluation of data and maps for each area

The existing data have been collected for many different purposes: Groundwater abstractions and protection, raw material qualities and quantities, geotechnical and construction reasons, scientific investigations, protection of the natural environment, e-

nergy exploration and supply, and so on. Therefore, the data supply is heterogeneous and a major exercise on data formatting and interpretation is requisite before data can be combined into the needs of this project. Also the simple question of combining field data, geophysical and borehole data from different databases and archives is demanding.
Geological terminology is not a problem because most geological institutions, companies and societies in Denmark are working after the same guidelines.

6.6 Combination of data and maps

Point data (boreholes, logs) are combined with area data on maps, which gives a better and more detailed picture of the (geological etc.) conditions near the ground surface. The conditions down to 100 meters below ground surface calls for problems. The boreholes are nearly always too few and only in areas covered by shallow geophysics it is possible to give a really good model for the distribution of different kind of layers and the geological development at the site. The prediction of the layers down to 100 meters may be based on interpretation of all the available information, which will be done by experienced geologists.

6.7 Description and presentation of data, areas and localities

Each of the approx. 20 areas will be described on basis of the available data. Therefore, some areas are treated more detailed than others. Probably, not all selected areas will fulfil all the demands. Nevertheless, the areas *will* be chosen *if* a large amount of information points to the disposal potential of the localities. The areas will be larger than the final localities are expected to be. The next step is to find the most potential localities. In each individual report, some recommendations concerning the individual areas will be put forward but there will no priority considerations between the areas.

6.8 Final remarks

Hopefully, the selected areas will fulfil as many of the listed criteria as possible. A uniform geographical distribution of the potential areas is not a criterion but it is suitable for the further selection process, that several regional possibilities exist.

7. Literature, database and homepages

7.1 Literature

Abrahamsen, N., 1967: I Aalborg er nedtaget hvad som var opsat paa hylder. Danske Jordskælv. Varv nr.1, 24-31.

Andersen, L.J. & Gravesen, P., 1989: Cyclogram Maps in the Interpretation of Pumping Tests. In: Moore, J.E., Zaporozec, A., Csallany, S.L. & Varney, T.C. (eds.). Recent Advances in Groundwater Hydrology. American Institute of Hydrology, 589-604.

Atomenergikommissionen, 1976: Affald fra kernekraftværker. Handelsministeriet april-maj 1976, 133 pages.

Binzer, K. & Stockmarr, J., 1988: Geologisk kort over Danmark. 1:500.000. Prækvartæroverfladens højdeforhold. Danm. Geol. Unders. Kortserie nr. 44, 10 pages.

Bondesen, E., 2001: Danske jordskælv – en rystende historie. GeologiskNyt 6/01, 36-39.

Dala, N.S. & Knudsen, T., 2009: Veje til en hydrologiegnet højdemodel. Danish Ministry of the Environment. National Survey and Cadastre, Technical Report No. 07, 10 pages,

Dinesen, A., Michelsen, O. & Lieberkind, K., 1977: A survey of the Paleocene and Eocene deposits of Jylland and Fyn. Geol. Surv. of Denmark Serie B, No. 1, 15 pages + appendices.

Ernstsen, V., Jakobsen, P.R., et al., 2006: Beregning af nitrat-reduktionsfaktorer for zonen mellem rodzonen og frem til vandløbet. Data og metode for 1. generationskortet. Denm. and Greenl. Geol. Survey Report 2006/93.

Finnish Energy Industries, 2007: Nuclear Waste Management in Finland, 15 pages.

Gravesen, P. & Fredericia, J., 1984 (eds.): ZEUS geodatabasesystem. Borearkivet. Databeskrivelse, kodesystem og sideregistre. Danm. Geol. Unders. Serie C, No.3, 259 pages.

Gravesen P. & Rasmussen, L.Aa, 1988: Geologisk kort over Danmark. 1:50.000. Kortbladet 1812 III og IV Bornholm. Danm- Geol. Unders. Kortserie nr. 4, 2 pages.

Gravesen, P., Binderup, M., Jakobsen, P.J. & Rasmussen, E.S., 2006: Geologisk set – Det sydlige Jylland. En beskrivelse af områder af national geologisk interesse. GEUS, Skov- og Naturstyrelsen og Geografforlaget, 188 pages.

Gravesen, P., Pedersen, S.A.S, Klint, K.E.S. & Jakobsen, P.J., 2008: Geologiske kort i Danmark – hvad viser de kvartærgeologiske kort. GeologiskNyt 2, 2006, 10-14.

Gravesen, P. & Rosenberg, P. (eds.), 2009: Særligt pesticidfølsomme lerområder: Datagrundlag og mulige veje mod zonering. KUPA. Danm. og Grønl. Geol Unders. Særudgivelse, 70 pages + appendices.

Hansen, S. & Milthers, K., 1954: Geologisk kort over Danmark. Hovedlinier I det kvartære landskab. Danm. Geol. Unders.

Haakansson. E. & Pedersen, S.A.S., 1992: Geologisk kort over den danske underground. 1:500.000. Varv.

IAEA, 1994: Siting of Near Surface Disposal Facilities. Safety Guides. Safety series no. 111-G-3.1, 37 pages.

IAEA, 1999: Near Surface Disposal of Radioactive Waste. Requirements. IAEA Safety Standards Series No. WS-R-1, 29 pages.

IAEA, 2005: Borehole Facilities for the Disposal of Radioactive Waste. IAEA Safety Standards Series, 102 pages.

Indenrigs- og Sundhedsministeriet, 2007: Beslutningsgrundlag for et dansk slutdepot for lav – og mellemaktivt affald. Udarbejdet af en arbejdsgruppe under Indenrigs- og Sundhedsministeriet, april 2007, 47 pages.

Jørgensen, F. & Sandersen, P., 2009: Kortlægning af begravede dale in Danmark, opdatering 2007-2009. Danm. og Grønl. Geol. Unders. Rapport, Særudgivelse fra GEUS, 374 pages.

Klint, K.E.S. & Gravesen, P., 1999: Fractures and Biopores in Weichselian Clayey Till Aquitards at Flakkebjerg, Denmark. Nordic Hydrology 30, 267-284.

Knudsen, P. & Vognsen, K., 2010: Metode til at følge vandstandsstigningstakten i de danske farvande. Danish Ministry of the Environment, National Survey and Cadastre, Technical Report No. 08, 25 pages.

Larsen, G., Frederiksen, J., Villumsen, A., Fredericia, J., Gravesen, P., Foged, N., Knudsen, B. & Baumann, J., 1988: Vejledning i Ingeniørgeologisk prøvebeskrivelse. Bull. Danish Geotechnical Society no. 1, 144 pages.

Mielby, S. (ed.), 2009: Den nationale grundvandskortlægning i Danmark. Faglige resultater 2009.

Minister for Health and Prevention, 2009: Redegørele om Beslutningsgrundlag for et dansk slutdepot for lav - og mellemaktivt affald, 13 pages.

Pedersen, S.A.S. (ed.), 1989: Danmarks jordarter i 1:200.000. Fire kortblade. Danm. Geol. Unders.

Pedersen, D., 2004: En geologisk og hydrogeologisk undersøgelse af inhomogeniter i moræneler. Speciale afhandling, Geologisk Institut, Køvenhvans Universitet.

Pedersen, S.A.S. & Petersen, K.S., 2002: Geologisk kort over Danmark. 1:50.000. Hanstholm. Danm. og Greenl. Geol. Unders.

SKB (Svensk Kärnbräslehantering AB), 2007: RD&D Programme 2007. Programme for research, development and demonstration of methods for the management and disposal of nuclear waste, 510 pages.

Smed, P., 1979, 1981, 1982: Lndskabskort over Danmark. A4 format (Approx. 1:333.000) and A2 format (approx. 1.166.000). Geografforlaget.

Stockmarr, J., 2005: Groundwater quality monitoring in Denmark. Bull. Geol Surv. Denmark and Greenland, 7, 33-36.

Wemaere, I, Marivoet, J. & Labat, 2008: Hydraulic conductivity variability of the Boom Clay in north-east Belgium based on four core drilled boreholes. Physics and Chemistry of the Earth 33, 24-36.

7.2 Databases

At GEUS:

Gerda Database
Jupiter Database
Modeldatabase
Reportdatabase

7.3 Home pages

Denmark:

Begravede dale ved GEUS:

www.begravededale.dk

By- og Landskabsstyrelsen:

www.blst.dk

Dansk Metereologisk Institut:

www.dmi.dk

GEUS:

www.geus.dk

Videncenter for klimatilpasning:

www.klimatilpasning.dk

Kort- og Matrikelstyrelsen:

www.kms.dk

International:

International Atomic Energy Agency (IAEA)

www.iaea.co

Wold Nuclear Association (WNA)

www.wold-nuclear.org

Posiva Oy, Finland

www.posiva.fi

Svensk Kärnbränslehantering AB (SKB), Sweden

www.skb.se

The interior from the final repository for low- and intermediate-level operational waste at Formark, Sweden (From SKB, 2007). The waste is deposited in a rock cavern without shielding in Precambrian basement.