DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2011/44

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report no. 4

Characterization and description of areas Bornholm

Peter Gravesen, Bertel Nilsson,
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1. Introduction

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

The investigation of geological deposits as potential waste disposals for high radioactive waste from nuclear power plants has earlier been focused on deep seated salt deposits and basement rocks, but the Tertiary clays were also mapped (Atomenergikommissionen, 1976, Dinesen, Michelsen & Lieberkind, 1977). The salt diapirs and the salt deposits are not included in the present study. The task is to find approximately 20 areas where a waste disposal potentially can be located. The 20 areas have to be reduced to 2–3 more precise locations, where detailed field investigations of the geological, hydrogeological-hydrochemical and technical conditions will be performed. The present report describes areas 1 and 2 on Bornholm, East Denmark.

2. Background

In Denmark, many different fine-grained sediments and crystalline rocks occur from the earth surface down to 300 meters depth. Therefore, the possible geological situations include sediments and rocks of different composition and age and these are also geographical distributed over large areas of Denmark. These sediments and rocks are shortly described - based on existing information - in Report no. 2, where four different types are included. 1: Crystalline granites and gneisses of Bornholm because in many other countries these rocks types are host for waste disposals. 2: Sandstones and shales from Bornholm as these sediments have fracture permeability, 3: Chalk and limestone because these sediments both act as groundwater reservoirs but in areas are low permeable seals. 4: Tertiary fine-grained clay deposits which are widely distributed, low permeable and can reach large thickness, 5: Fine-Grained Quaternary clays from interglacial, glacial or Holocene times.

All the Danish sand and gravel deposits are excluded from the description because of their potential as ground water reservoir, high permeability, low sorption possibilities and low protection conditions. The sand and gravel deposits often occur below or above the described low permeable and fractured deposits and sand layers can be intercalated in them. Therefore, in certain situations sand and gravel sediments are included in the final descriptions.

3. Data and methods

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

Gravesen et al. (2010, in Report no. 1), describes briefly the existing data collections including databases, maps and models which have been used during the work of selection of approximately 20 potentially suitable areas. Most of the information is stored in GEUS databases: Borehole data and co-ordinates, rock sediment and ground water compounds, maps, geophysics and much more, but information are also collected from other institutions.

The methods are described in more details and the description is the directly background for the selection of the sites.

4. Selection of areas

Selection of potential areas on Bornholm has to fulfil the criteria and answer the questions described and put forwards in Gravesen et al., (2010, Report 1 and 2).

The areas chosen on Bornholm are only related to Precambrian basement rocks on northern parts of the island. Basement rocks are used for waste disposals in Sweden and Finland, both near-surface disposals and deep seated geological disposals. At Forsmark (Sweden), near-surface disposals are found in caverns or tunnels 50 m below surface.

Therefore it is relevant to investigate and analyse some of the basement rocks in relation to potential disposal areas.

5. Area 1. Østermarie – Paradisbakkerne, north east Bornholm

5.1 The location of the area

Bornholm is located in the Baltic Sea south of Sweden. Area 1 is found in the north east corner of Bornholm (Fig. 1). The geology of the area is characterized by hard, low permeable, crystalline Precambrian basement rocks (gneisses) covered by sandy and clayey tills from the last ice age, the Weichselian.

Figure 1. Location of the area. Bornholm is located in the Baltic Sea, east of the mainland Danmark.

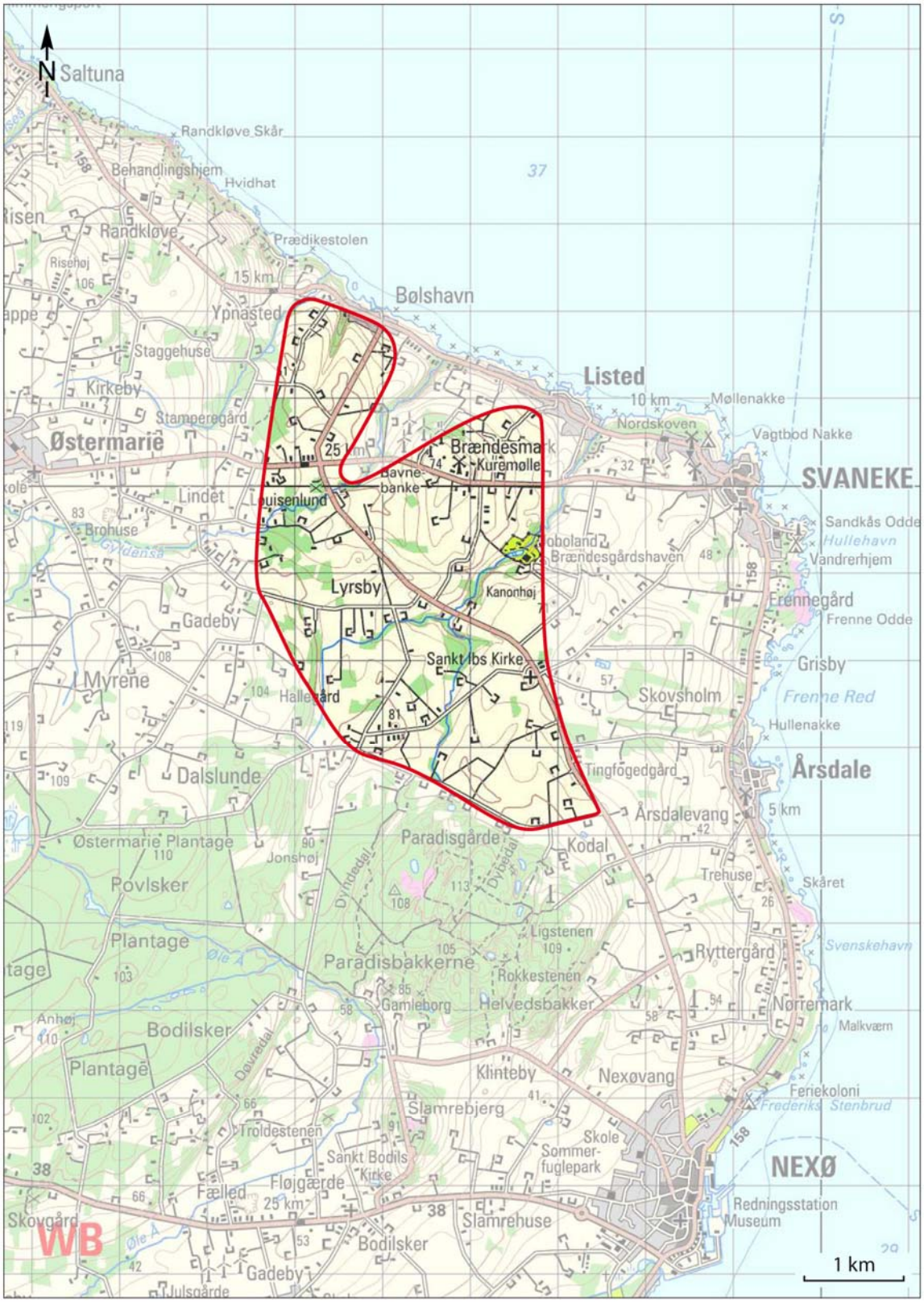


Figure 2. A detailed map of Area 1. The area is located on the north-eastern part of Bornholm.

In Fig. 2, the area is delineated by a red line and hatching. The area is bordered towards the east by the Svaneke Granite and the boundary between the granite and the Bornholm Gneiss/Paradisbakke Migmatite is found west of Listed. Towards the north, the boundary is the Baltic Sea. Towards the west, the boundary is a line from Saltuna to east of Østermarie to the north-western corner of the Paradisbakkerne. The west-east border line is from the corner to Paradisgårde along the rim of Paradisbakkerne (Fig. 2).

5.2 Terrain, topography and surface processes

The area is located on the north-eastern part of Bornholm, between the coast and the northern foot of the high-lying basement terrain Paradisbakkerne. The size of the area is almost 15 km^2. The overall impression of the landscape is a gently smoothed terrain, which is undulating, but the hills are few and large and the slopes are long and only weakly dipping. The top-level of these landscape elements are located c. 65 – 80 m above sea level and the slope of the hillsides is some 15 – 20 meters over 2 – 4 km, equivalent to slopes of only c. ½ – 1 %. Most of the area is characterized by "slopes" of this size. A little steeper slopes, up to c. 5 %, are found locally, e.g. at the hill Bavnebanke and along the streams.

The area is traversed by NE-SW oriented streams running out into the Baltic Sea north of Bornholm. The streams are relatively straight with narrow river valleys. Except for a very small, artificially dammed lake at the amusement park Brændegårds-haven, the area does not include lakes.

Roughly estimated, c. 10 % of the land area is covered by small woods and scrubs (along the streams). The remaining and predominant part of the area is used for agriculture with scattered houses. The area is crossed by a few main roads and many small, local roads. Owing to the low relief and the relatively intense cultivation, the surface processes (soil creep, frost – thaw processes, soil development etc.) proceed slowly and undramatic. The discharge of the streams is expected to resemble the discharge pattern of other "fracture valley streams", which means that the discharge is marked by a very pronounced variation during the year.

5.3 Surface geology and profiles

The surface geology is dominated by a Quaternary cover consisting of clayey and sandy tills over gneissic and migmatitic rocks and only few outcrops. Just outside the area, the Præstebo and Bertelegaard quarries, located in the rim of the Paradisbakkerne area, demonstrate the rocks and structures (Figs. 3 and 4). The Paradisbakkerne is a higher area (up to 113 m above sea level) cut by a series of NE-SW oriented linear

fracture valleys (“Sprækkedale”). Area 1 is situated in front of the Paradisbakkerne towards the northeast and is a plane area at least 10-20 m below the top of Paradisbakkerne.

The area is crossed by a number of recent streams running out into the Baltic Sea and these are probably located in fracture or fault zones in the basement as the stream courses and their valleys are orientated in same direction as the fracture valleys (Fig. 16). The easternmost and largest stream, Vaseå, is running out east of Listed. Gyldenså is running out east of Bølshavn while five smaller brooks are located between Bølshavn and Saltuna.

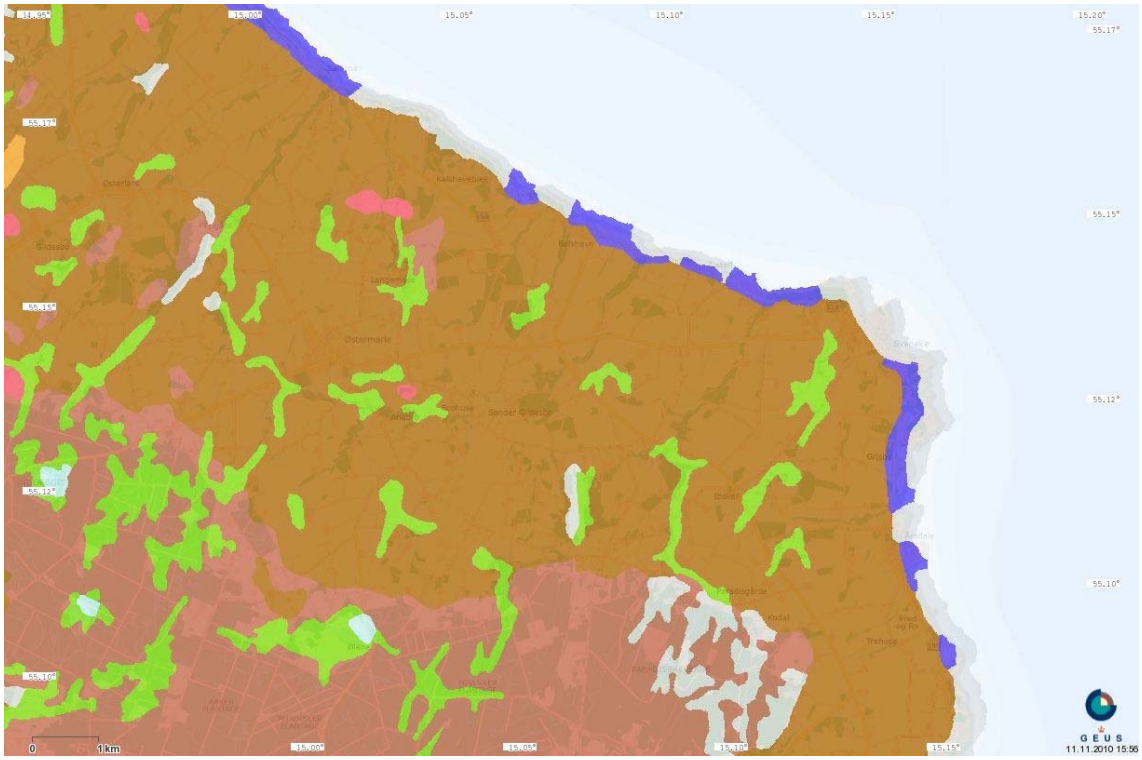


Figure 3. Map of the Quaternary deposits (From GEUS Homepage after Pedersen, 1989). Legend: Brown: Clayey till, Red Brown: Sandy till, Red: Meltwater sand and gravel, Blue: Late Weichselian marine deposits, Green: Holocene freshwater deposits, White: Precambrian basement.

Figure 4. Orthophoto of the northern rim of the Paradisbakkerne showing the migmatite quarries at Præstebo and Bertelegaard. The Quarries are partly filled with water and look like small lakes on the photo (From GEUS Home page).

5.4 Boreholes

The area is penetrated by c. 50 boreholes (Fig. 5). The drilling method normally produce very poor samples of the Precambrian rocks which are crushed but the overlying layers give fair samples of the Quaternary sediments.

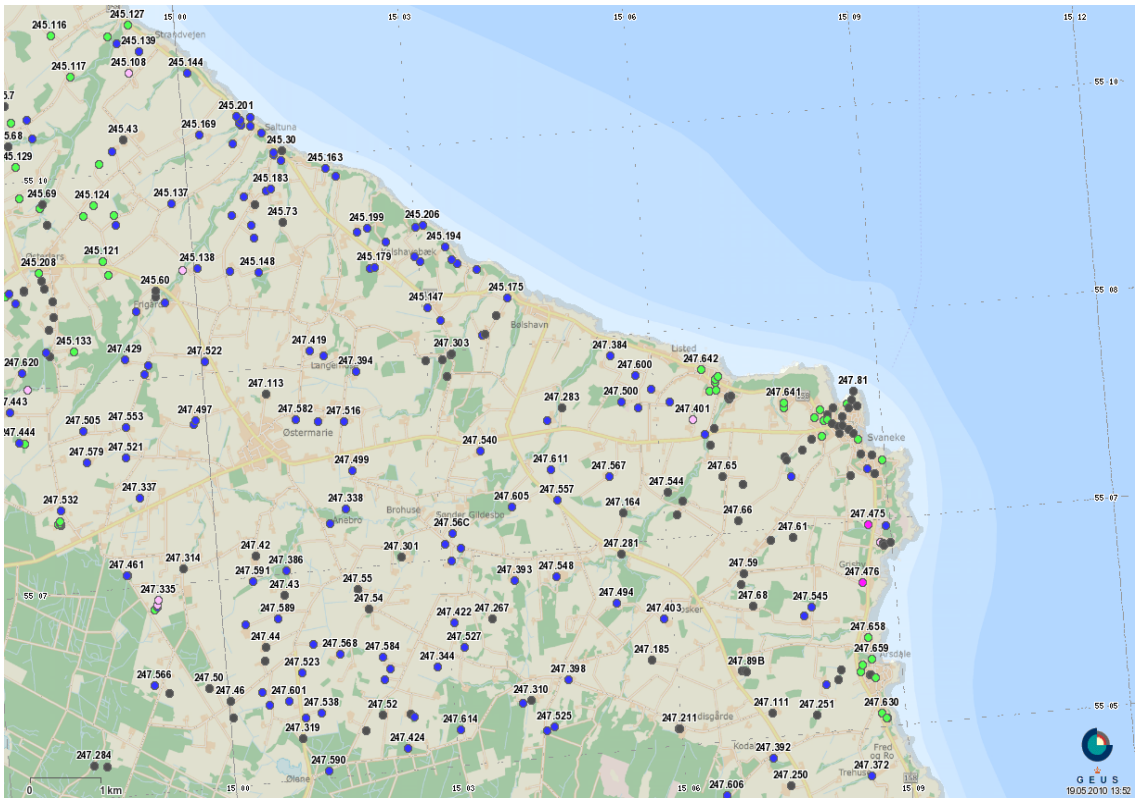


Figure 5. Location of boreholes in the area. (From GEUS Jupiter Well Database). Legend: 247.344: Database archive no., Blue dots: Water supply well, Black dots: Unknown purpose, Green dots: Other Boreholes, Pink dots: Raw material borehole, Light red dots: abandoned borehole, Orange dots: Geotechnical borehole.

Most of the boreholes are wells which supply households, smaller farms and other local needs. Many wells are shallow, some are dug, but because of the need for the optimal water supply, the wells have to reach groundwater filled fractures. Some wells are as deep as 60 – 80 m and a few reach down to 145 m deep (Fig. 6).

De Nationale Geologiske Undersøgelser for Danmark og Grønland

Udskrevet 19/5 2010 Side 1

BORERAPPORT

DGU arkivnr: 247. 548

Borested : Lyrsbyvej 40, Østermarie
3740 Svaneke
Erstattet af 247.661

Kommune : Bornholm
Region : Hovedstaden

Boringsdato : 5/8 1987 **Boringsdybde** : 61 meter **Terrænkote** : 69.7 meter o. DNN

Brøndborer : Bornholms Brøndboring v/B.O. Phil
MOB-nr : 10164
BB-journr : 380
BB-bornr :

Prøver
- modtaget : 10/12 1987 **antal** : 3
- beskrevet : 30/12 1987 **af** : PG
- antal gemt : 0

Formål : Vandforsyningsboring **Kortblad** : **Datum** : ED50
Anvendelse : Vandforsyningsboring **UTM-zone** : 33 **Koordinatkilde** :
Boremetode : Tørboring/slagboring **UTM-koord.** : 504850, 6108538 **Koordinatmetode** : Dig. på koor.bord

		Ro-vandstand	Pejledato	Ydelse	Sænkning	Pumpetid
Indtag 1	(seneste)	1.2 meter u.t.	22/3 1989	2 m³/t	0 meter	2 time(r)

Notater : Halvdelen af tilstrømning fra 59 m!

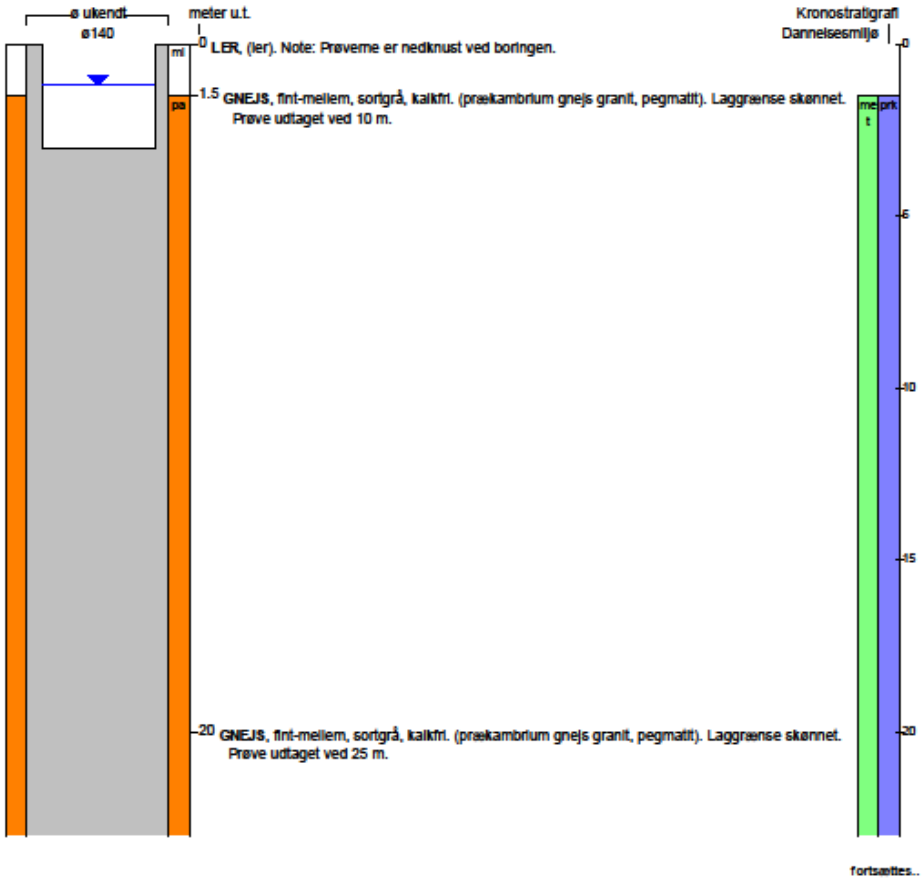


Figure 6. Borehole DGU no. 247.548 from the Jupiter Database at GEUS. Upper part of the 61 m deep borehole. The groundwater table was situated 1.2 m below ground surface when the borehole was drilled.

5.5 Sediment and rock characteristics, mineralogy and chemistry

The description will first deal with the deposits older than the Quaternary (that is to say older than 2.6 million years), the pre-Quaternary, which consists of the more than 630 million years old Precambrian crystalline basement rocks.

5.5.1 Pre-Quaternary rocks

The rocks in the area are of two types: Bornholm Gneiss and Paradisbakke Migmatite. Because of very poor exposition of the rocks, it is difficult to give exact distributions and boundaries between the two rocks types. One distribution without boundaries is seen on the map, Fig. 7, but other authors indicate a more limited distribution of the Paradisbakke Migmatite. Generally, the gneiss is located towards the west and north.

The Paradisbakke Migmatite (described as gneiss by some authors) is best exposed in the Præstebo and Bertelegaard quarries located at the rim of the Paradisbakkerne (Fig. 4) while the Bornholm Gneiss is exposed along the coast from Listed to Saltuna where the boundary between the gneiss and the Svaneke Granite can be recognized.

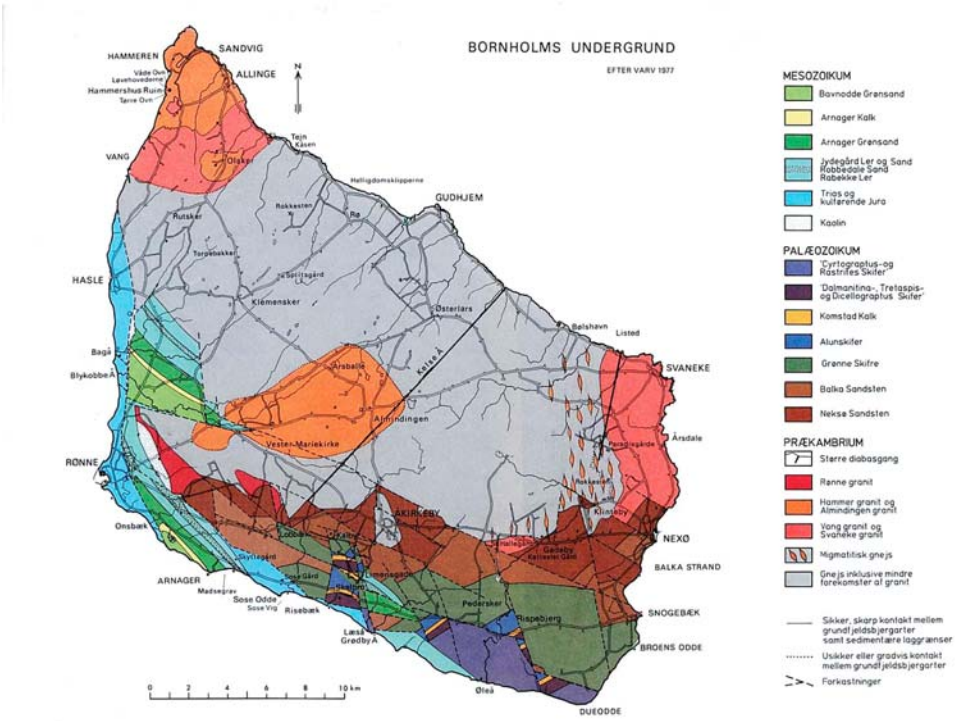


Figure 7. Map of the pre-Quaternary surface which shows the older rocks and sediments below the Quaternary sediments. Some major fault lines and diabase dikes are also shown (From Varv, 1977). Legend: Prækambrium: Precambrian (grey and red colours), Palæozoikum: Palaeozoic, Mesozoikum: Mesozoic. The various rock and sediment units are recognized with different colours.

Bornholm Gneiss:

Mineralogy

The Bornholm Gneiss, mainly medium-grained, consists of several gneiss types (Fig. 8 and 9):

Grey biotite gneisses are weakly foliated or foliated and occasionally banded of light and dark bands: Quartz 29 %, plagioclase 31 %, perthite 28 %, biotite 8 %, hornblende 1 %, sphene 1 % and traces of epidote, chlorite and ore.

Granitic grey foliated biotite gneiss: Quartz 25 %, plagioclase 27 %, perthite 38 %, biotite 5 %, sphene 1 %, chlorite 1 % and traces of hornblende, epidote and ore.

Quartz rich gneisses: Quartz 53-72 %, plagioclase 22-12 %, perthite 19-11 %, biotite 2-1 %, hornblende 1 %, muscovite 2-1 % and traces of sphene and epidote.

Skarn bearing biotite gneisses are grey biotite gneisses containing ellipses of garnet-epidote.

Quarzites are almost pure quartz rocks and occur often as layers in grey biotite gneisses.

The colours of the gneisses are grey and pale grey but in places reddish.

Figure 8. Folded Bornholm biotite gneiss west of Listed.

Figure 9. Schistose Bornholm gneiss west of Listed.

The gneisses often contain other rock types as the granite near Østerlars (Fig. 10).

Weathering

Weathering of the gneiss can be seen along the north coast of Bornholm where the gneiss is in daily contact with sea water.

Figure 10. Medium-grained red grey granite in the gneiss area at Østerlars.

Paradisbakke Migmatite

Mineralogy

The medium-grained Paradisbakke Migmatite consists of quartz 23 %, alkali feldspar 35 %, plagioclase 25 %, hornblende 8 %, biotite 7 %, sphene, 1 %, ore 1 %, and traces of apatite and flourite including up to 2–3 cm large, black radioactive allanite/gadolinite minerals in pegmatites. The migmatite is separated into a basal dark grey fine-grained part (80 %) with greenish plagioclase (Fig. 11) and light lenses (ca. 20 %). These ill-defined veins consist mainly of quartz, alkali feldspar and plagioclase and are often white or light red. This gives the rock a characteristic foliated flame look.

Other lenses contributing to the gneisses and the migmatite are coarse-grained pegmatitic and fine-grained aplitic veins as smaller isolated bodies (Fig. 12) or as larger longer pegmatite veins (Fig. 13). The pegmatites and aplites contain 30–40 % quartz, 45–60 % perthite, 10–20 % plagioclase and low content or traces of dark minerals ore, sphene, apatite, epidote and fluorite including gadolinite.

Figure 11. Grey and red, foliated, flame Paradisbakke Migmatite from Præstebo Quarry, the northern rim of the Paradisbakkerne area.

Figure 12. Thin red grey pegmatite vein in the Paradisbakke Migmatite, Bertelegaard, northern rim of Paradisbakkerne.

Figure 13. A long red grey pegmatite vein in the Paradisbakke Migmatite, Bertelegard Quarry, northern part of Paradisbakkerne.

On Bornholm, more than 250 diabase dykes and approx. 20 sandstone dykes occur in the basement. Area 1 is crossed by diabase dyke intrusions as by the 30 m thick Listed dyke of olivine basalt with direction towards the NNW-SSW. This dyke can be traced 5 km from the start in the Svaneke Granite to the Tamperdal in the Paradisbakkerne where it cuts the Paradisbakke Migmatite. In the area, other diabases are cutting both the gneisses and the migmatite, and black and pale green weathered diabase is reached down to 60 m below surface in borehole DGU no. 247.402 (the Listed Diabase?). In DGU no. 247.398, diabase is encountered from 22 to 69 m below surface and in DGU no. 247.557 diabase is reached from 28 to 43 m below surface.

Weathering
The weathering of the migmatite is only developed in connection with fracture zones where iron minerals are oxidised.

5.5.2 Quaternary deposits

The Quaternary sediments in the area consists mainly of glacial tills deposited during the Weichselian (the last glacial). The cover over the Precambrian rocks seems to be rather continuous (Figs. 3 and 14). Nevertheless, the thickness varies from no cover in a few places to 17 m in small stream valleys. In the Præstebo and Bertelegaard quarries, the migmatites are overlaid by sandy and clayey, often very gravely and stony, tills (Fig. 15). Samples from the boreholes also show a dominance of clayey tills described

as sandy, weakly gravely, yellow brown and olive brown and calcareous in the upper app. 3 m and silty and weakly gravely, olive grey and calcareous down to the basement. There are no investigations of eventually fractures in the tills in the area but the oxidized characters of the tills indicate the occurrence of fractures.

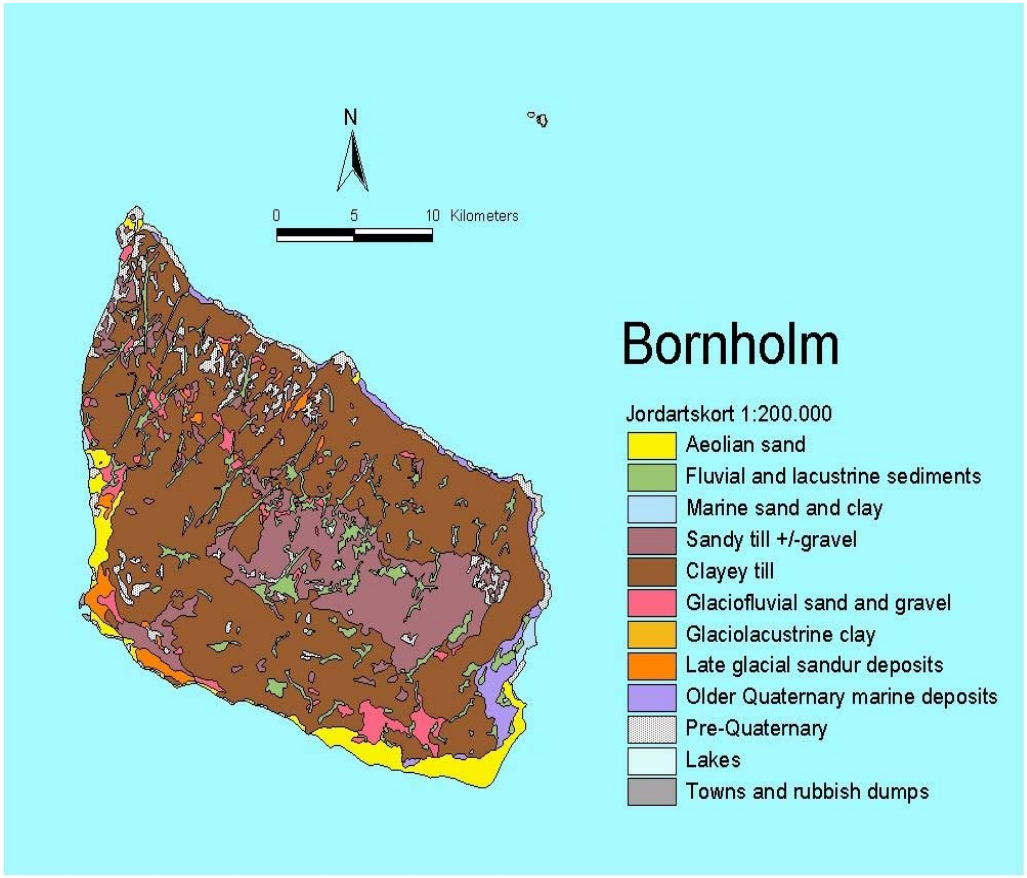


Figure 14. Map of the Quaternary surface deposits. Original scale 1:200.000. (After Pedersen, 1989).

Figure 15. In the Præstebo Quarry only a thin cover of Quaternary sandy till occur over the migmatite.

5.6 Tectonics, structures and seismic activity

5.6.1 Major tectonic structures

The main linear structural elements of Bornholm are the faults, the linear valleys and the diabases.

The faults cross the basement rocks with orientations NE-SW, NNE-SSW and WNW-ESE. Most of the registered faults are found in the Svaneke Granit-Gneiss /Paradisbakke Migmatite area, the Hammer Granite/Vang Granite area and in the

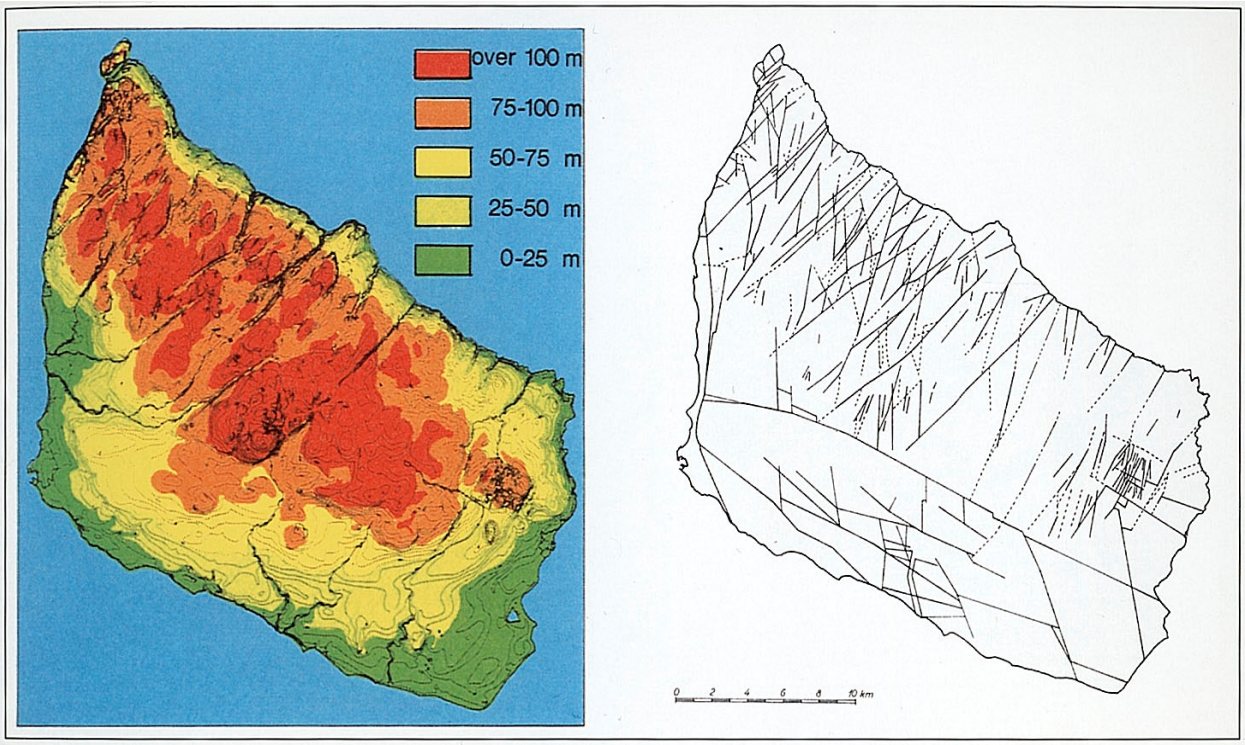
boundary between the basement and the Paleozoic and Mesozoic sediments. A major fault follows the northern rim of Paradisbakkerne (Fig. 7).

The linear valleys and the large fracture zones in the Paradisbakkerne are mainly oriented NE-SW and NNE-SSW. These directions are parallel to directions of the other large valleys in the basement and some of the major faults in the Svaneke granite and gneisses. Some valleys are oriented nearly perpendicular to the first valleys with orientations of WNW-ESE which is parallel to directions of the major faults in the basement and Paleozoic sediments. The valleys represent fault lines in the granites and gneisses. They are formed by erosion of the Quaternary glaciers which moved over and crushed basement material from the linear fault zone. The concentration of valleys north of Paradisbakkerne is lesser than in other parts of the basement (Fig. 16).

Another indication of the major structures is the courses of the streams and brooks. The lower course of easternmost Vaså, Gyldenså and two brooks are oriented NE-SW but the upper courses start with WNW-ESE directions before turning towards the north. The western three brooks just east of Kelse Å are oriented NNE-SSW. All these directions are the same as the faults and valleys and show that the streams and brooks are located in fault zones.

The diabase dykes are oriented in the same directions as the valleys and the faults and some dykes are intruded into the bottom of the valleys. The Listed dyke strikes 16^{o} E with dip 86^{o} and the Bølshavn dyke strikes 12^{o} E with dip 80^{o}. Sandstone dykes crosses the diabases at Listed. As indicated above, more dykes occur in the area and these dykes have probably the same orientations as the Listed and Bölshavn dykes. The dykes with NE-SW orientation are of Precambrian age while the more E-W and ENE-WSW oriented dykes probably are from Permian. The sandstone dykes are formed in Cambrian.

The gneisses and granites in the area are folded as can be seen by the many small fold structures. The fold axes are mainly oriented NE-SW and N-S, dipping towards NE and N. An “East Bornholm Fold” was been proposed in 1961 based on old and new field data but later on the existence of this fold has been rejected.



a. b.

Figure 16. a. Topography of Bornholm. b. Major faults and valleys in the basement and the younger sediments towards the south and the west (From Gravesen, 1996).

5.6.2 Fractures

The crystalline rocks on Bornholm are all cut by several systems of fractures and joints alternating in size and distribution. Along some of the fractures, smaller displacements (in the scale of a few to tens of centimetres) can be recognized and they may be classified as faults. Often these small faults display surfaces with slicken-side lineation. Furthermore, the basement rocks in the focused area comprise a strong fabric formed by the metamorphic foliation and fold structures.

Based on preliminary observations from Præstebo and Bertelegård quarries and the north coast of the area, the following is suggested (Figs. 17, 18 and 19).

Figure 17. Section of the Paradisbakke Migmatite in the Præstebo quarry (high approx. 12 m). Spacing's of prominent horizontal fractures are increasing downwards.

The thickest section of 12–15 m below surface is seen in fig 17. Some information about the deeper layers can be received from logs in Østermarie Water Work boreholes, just outside the area (Figs. 25 and 26). Gamma logs, Resistivity logs and Flow logs give indications of fracture zones and zones of weathering. High flow log values indicate fracture zones 19.0–22.0 m, 25.0–25.5 m and 37.0–37.5 m, High gamma values and low resistivity values indicate clay weathered rocks in fracture zones in e.g. 25 m, 29.5 m, 31 m and 36.7 m. The log types do not indicate the orientation of the fractures but the general picture is that the amount of fractures is decreasing below 25 m depth and is very low below 40 meters under the surface. High gamma values indicate pegmatites with high feldspar, mica and occasionally radioactive minerals. High iron values in the groundwater also indicate weathering of the gneiss. Moreover, weathered rocks in outcrops have often a high content of oxidised iron.

Figure 18. Section from Præstebo quarry with vertical and horizontal fractures. The spacing of the vertical fractures is changing from very small (cm size) to a spacing of several metres. Only one horizontal fracture is seen in the approx. 3 m high section.

Figure 19. Vertical fracture zone in Paradisbakke Migmatite, Præstebo Quarry.

5.6.3 Geological and structural models

The geological and structural model of the area is rather simple concerning lithology but complex in relation to the structural conditions (Figs. 20 and 21).
The model consists of two main lithological types:

A. Clayey and sandy tills which in some places are overlain by Holocene deposits.

B. The bedrock of Bornholm Gneiss or Paradisbakke Migmatite.

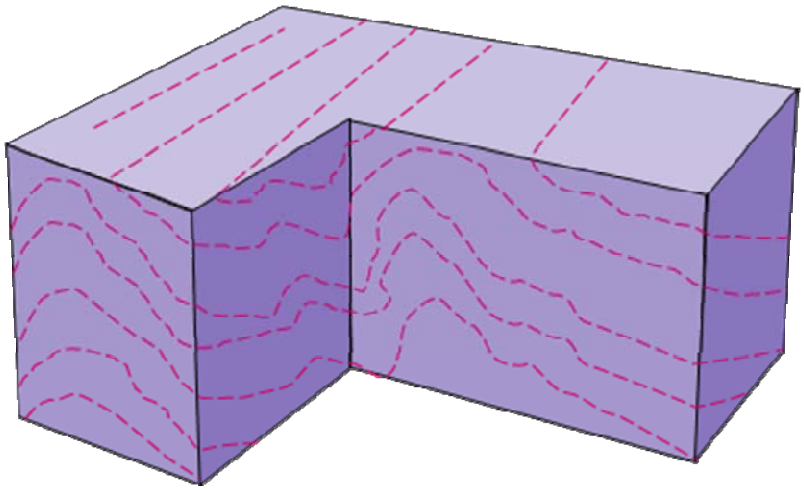
Details of the structural model of the area are as follows:

The model for the classification of the planar and linear fabric in the NE Bornholm area is mainly based on investigations along the north coast, where the Bornholm Gneiss are exposed in the rocky beach. In addition, detailed observations have been carried out in the Præstebo and Bertelegaard quarries, where the Paradisbakke Migmatite was quarried until 1988.

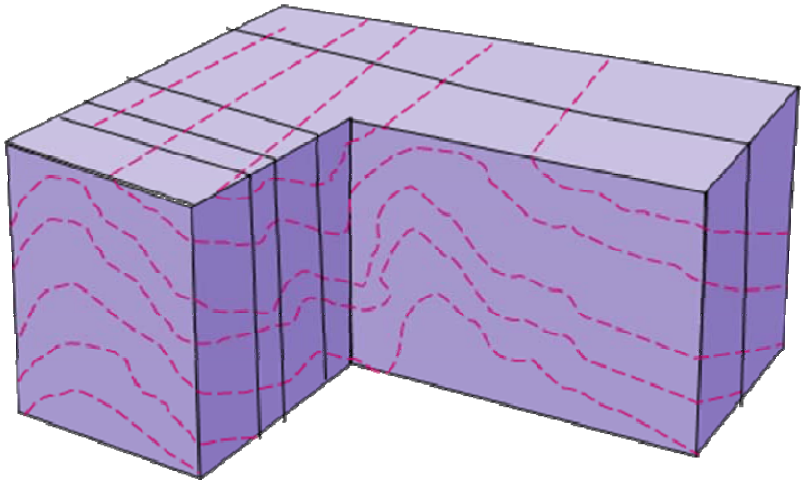
The earliest fabric in the rocks comprises a metamorphic foliation (main strike 170°), which is superimposed by shear folding (Fig. 20a). This metamorphic fabric creates a N-S orientated trend, which is the main direction of the boundary of the Paradisbakke Migmatite, and probably the fabric is also responsible for the northerly orientated trend of the walleyes and drainage systems. The second deformation phase is a strongly developed vertical jointing orientated ESE-WNW (main strike 118°) (Fig. 20b). Slickenside lineation observed on a few joint surfaces indicates a sinistral displacement towards 300°. This phase of jointing is interpreted as developed in the main phase of wrench faulting in the Sorgenfrei-Tornquist Zone in the Early Paleocene. The final phase of deformation is an anatomising framework of fractures orientated subhorizontally (Fig. 20c). This fracturing was created by the glacial shearing during the advance of the Baltic Ice Stream in the final phase of glaciodynamic impact in the last part of the Weichselian glaciation about 25–15.000 years BP.

The anatomizing fracturing of the surface is responsible for the glacio-morphological features known as rock moutonnée (Fig. 21). The till is in some places overlain by Holocene deposits. In general, it is expected to affect the basement rocks to a depth about 25 m below surface.

In the Præstebo area, the metamorphic fabrics are a general nature of the basement rock, which has no or very little effect on the hydrodynamic conditions in the subsurface. The spacing of the vertical jointing varies from cm to 5 m. This is the smallest frequency of vertical fractures recognized on Bornholm during the present investigation. The glaciotectonic fracturing resulted in rhombohedral shaped segments with the maximum thickness 1–3 m and a length in the order of 5–10 m. (Fig. 22)



a.



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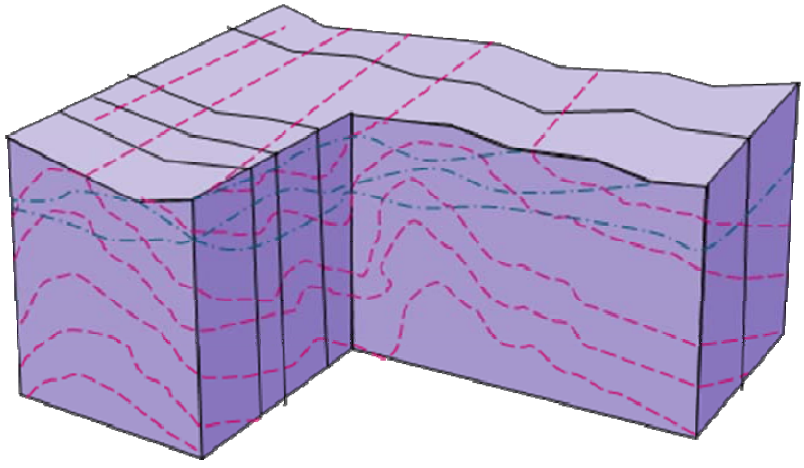

c.

Figure 20. Model of the geological and structural conditions of Area 1. a. Metamorphic foliation and folding of the migmatite. b. Second deformation with vertical jointing. c. Deformation by the Weichselian glaciers with subhorizontally fractures.

Figure 21. Section in Bornholm gneiss west of Listed. The exposure forms a rock mouton-née, a glaciomorphological feature formed by Weichselian glaciers.

Figure 22. Paradisbakke Migmatite/Gneiss from the Præstebo Quarry, northern part of Paradisbakkerne. The migmatite/gneiss is cut by several vertical fractures but only by few horizontal fractures.

5.6.4 Earthquakes - seismic activity

The seismic activity in the Bornholm area - the island and the near surrounding sea - is very low (Fig. 23). Almost no seismic movements have been registered on Bornholm although a seismic station is located in Almindingen.

Therefore it is impossible to relate recent seismic activity to the many faults and fractures in the bedrocks, and other signs of recent movements along the faults and fractures have not been proven. The island is considered as very tectonic stable. The position of Bornholm in the Fenno-Scandian Border Zone could indicate seismic activity.

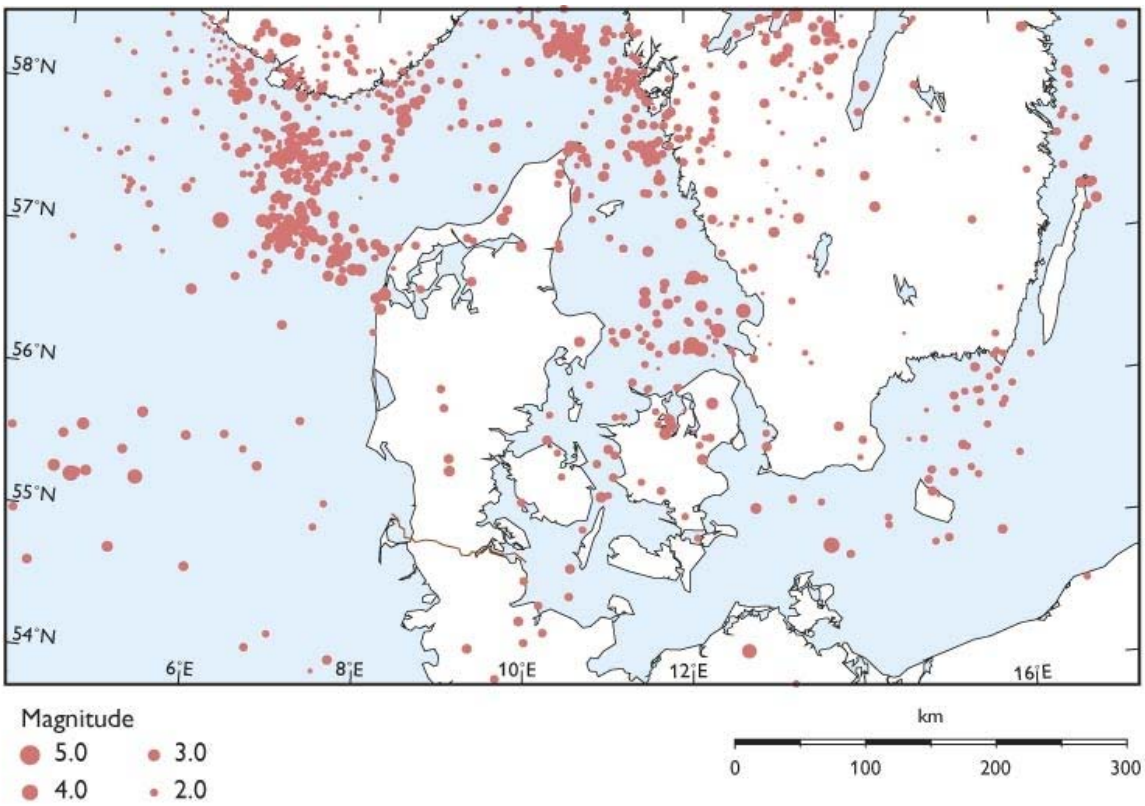

Figure 23. Seismicity in Denmark and surrounding areas 1970 to 2008. Epicentres are from GEUS earthquake catalogue and Catalogue of earthquakes in Northern Europe by University of Helsinki. All epicentres are determined using a minimum of three stations (After Larsen et al., 2008).

5.7 Ground stability

The ground stability of the area is very good. There are apparently no earthquake disturbances, no deposits of glacial sediments with glaciotectonic structure which could give unstable conditions and no slope where recent sliding of material can occur.

5.8 Groundwater hydrogeology

5.8.1 Groundwater characteristics

The East Bornholm site (Area 1) is positioned in an area that is characterized by presence of one shallow groundwater body (DK 3.1.1.1: Groundwater body Code of the Ministry of Environment) covering the entire Bornholm (Fig. 24) and one regional groundwater body (DK 3.1.2.3), that covers most of the northern part of Bornholm (Fig. 25). There is no deep groundwater bodies identified at the island Bornholm. The shal-

low groundwater body consists of meltwater sand deposits but the extension of the groundwater body is not very well defined. Based on lithological information from the JUPITER database, is it very likely that DK3.1.1.1 within Area 1 does have a very limited extension. The regional groundwater body DK3.1.2.3 consists of fractured basement rock that very likely covers the entire or most of the suggested Area 1. The subdivision into groundwater aquifers is thoroughly described by the former Bornholm Regionskommune in the basis analysis part 1. In addition, the Bornholm catchment management plan (Hovedvandopland 3.1) has been described by the Ministry of Environment. The overall assessment of the chemical and quantitative status of the regional and deep water quality is good (see Section 5.9).

Figure 24. Shallow (or terrain near) groundwater body DK3.1.1.1. Area 1 is placed North of Paradisbakkerne, and between Østermarie and Svaneke. (From Ministry of Environment, 2010)

Figure 25. Regional groundwater body DK3.1.2.3 on East Bornholm (From Ministry of Environment, 2010).

Only sparse information is available about the groundwater conditions in the area as no larger water works are located in Area 1. Most likely, the reason for this is, that no large fracture valley (sprækkedale) with meltwater sand and gravel and crushed bed-rock in the bottom is located within Area 1.

The groundwater aquifers located in the basement rocks are restricted to horizontal and vertical fracture zones in the bedrock. The rock matrix is expected to have very low porosity and fracture permeability. The water infiltration into the basement rock aquifers depends of the tightness of the Quaternary clay cover and the spatial framework of the fractures in the bedrocks. The groundwater flow in the fracture system has not been studied in detail at Bornholm.

Borehole logging has been carried out in the wells from Østermarie Water Work just outside Area 1. An example of the flow conditions in the 52 m deep borehole 247.496 (Fig. 26) in the gneiss can be seen in Fig. 27. The flow log shows that approx. 40 % of the inflow occurs between 25.0 and 25.5 m, approx. 20 % between 19.0 and 22.0 m and approx. 10 % between 37.0 and 37.5 m. Calculations show that approx. 30 % inflow happens between 7.0 m and 13.5 m depth. The boring has reached and crossed fracture zones in these intervals and apparently the largest inflow occurs within the upper 25 m. This pattern can also be demonstrated in other bedrock boreholes on Bornholm.

The net-precipitation over whole Bornholm is estimated to 350 mm per year and the reservoirs are quickly filled up after rain periods but most of the water is flowing directly into the sea because of the limited reservoirs. The groundwater level is often situated a few meters below terrain but in areas with pumping for the supply of drinking water, the draw down normally lowers the groundwater table to large depth (10–30 m) for a yield of a few 100 l pr. hour. No hydraulic tests have been done on the basement rocks in the areas between the large fault bounded valleys 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 was 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}.

Lately, the National Water Resources Model (DK-model) has been calibrated in the basement rocks with a horizontal bulk hydraulic conductivity value of 2.6×10^{-7} m/s of the upper approx. 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. The unsaturated zone is often thick as it is based on fracture permeability where the fracture spacing is high.

It is important to emphasize that a limited number of wells are drilled to depths between 100 m and 150 m and no wells are deeper than 180 m in the basement rocks at Bornholm. However, no hydraulic knowledge exists in the basement rocks at depths below 100 m at Bornholm.

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BORERAPPORT — **DGU arkivnr: 247. 496**

Borested : Østermarie vandværk, Nydamsvej 7, 3751 Østermarie
Kommune : Bornholm
Region : Hovedstaden

Boringsdato : 4/10 1983 — **Boringsdybde** : 52 meter — **Terrænkote** : 106.52 meter o. DNN

Brøndborer : Bornholms Brøndboring v/B.O. Phil
MOB-nr :
BB-journr :
BB-bornr :

Prøver
- modtaget : 12/4 1984 **antal** : 3
- beskrevet : 8/10 1984 **af** : PG
- antal gemt : 3

Formål : Vandforsyningsboring
Anvendelse : Vandforsyningsboring
Boremetode : Pneumatisk/DTH/odex
Kortblad :
UTM-zone : 33
UTM-koord. : 499164, 6108626
Datum : ED50
Koordinatkilde : Amt
Koordinatmetode : GPS

		Ro-vandstand	Pejledato	Ydelse	Sænkning	Pumpetid
Indtag 1	(seneste)	1.15 meter u.t.	1/12 2009	11 m³/t	1.2 meter	3 time(r)
	(første)	1.5 meter u.t.	6/11 1986			

Notater : Tørt fra 5 - 8 m, første vandførende lag 13 - 14 m

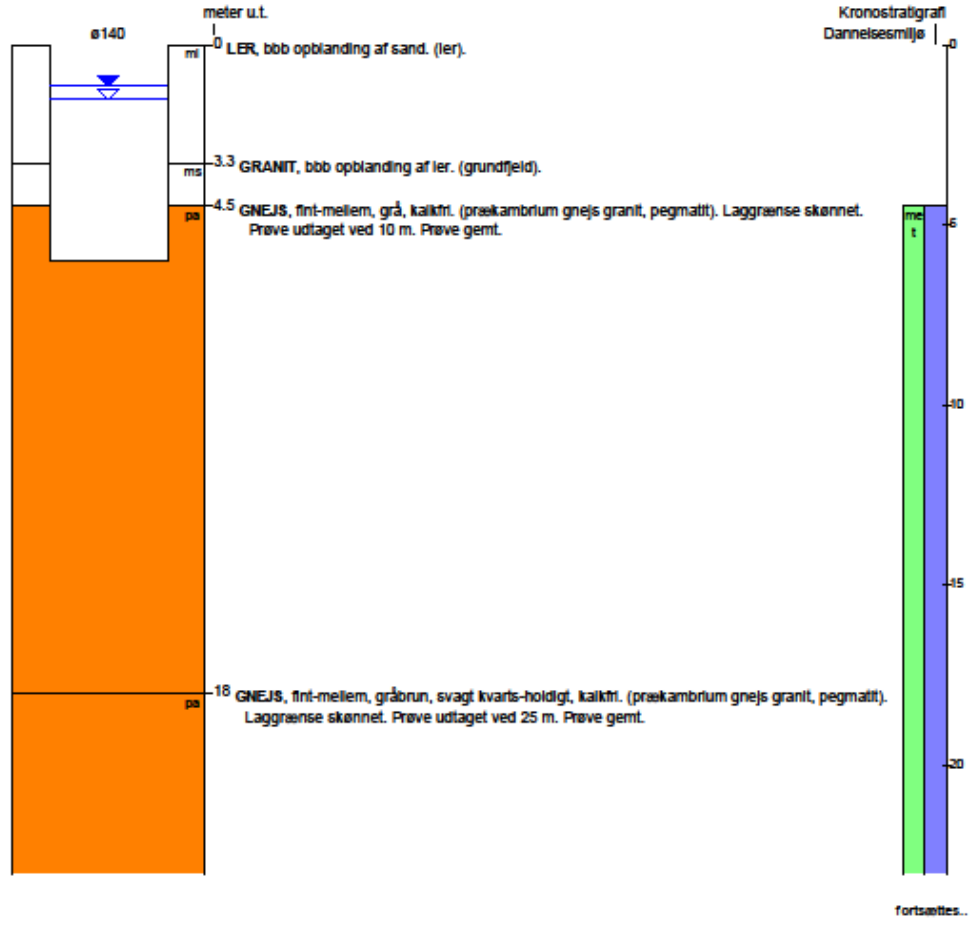

Figure 26. Borehole log from DGU no. 247.496. Upper part of the 52 m deep borehole (From the Jupiter Database).

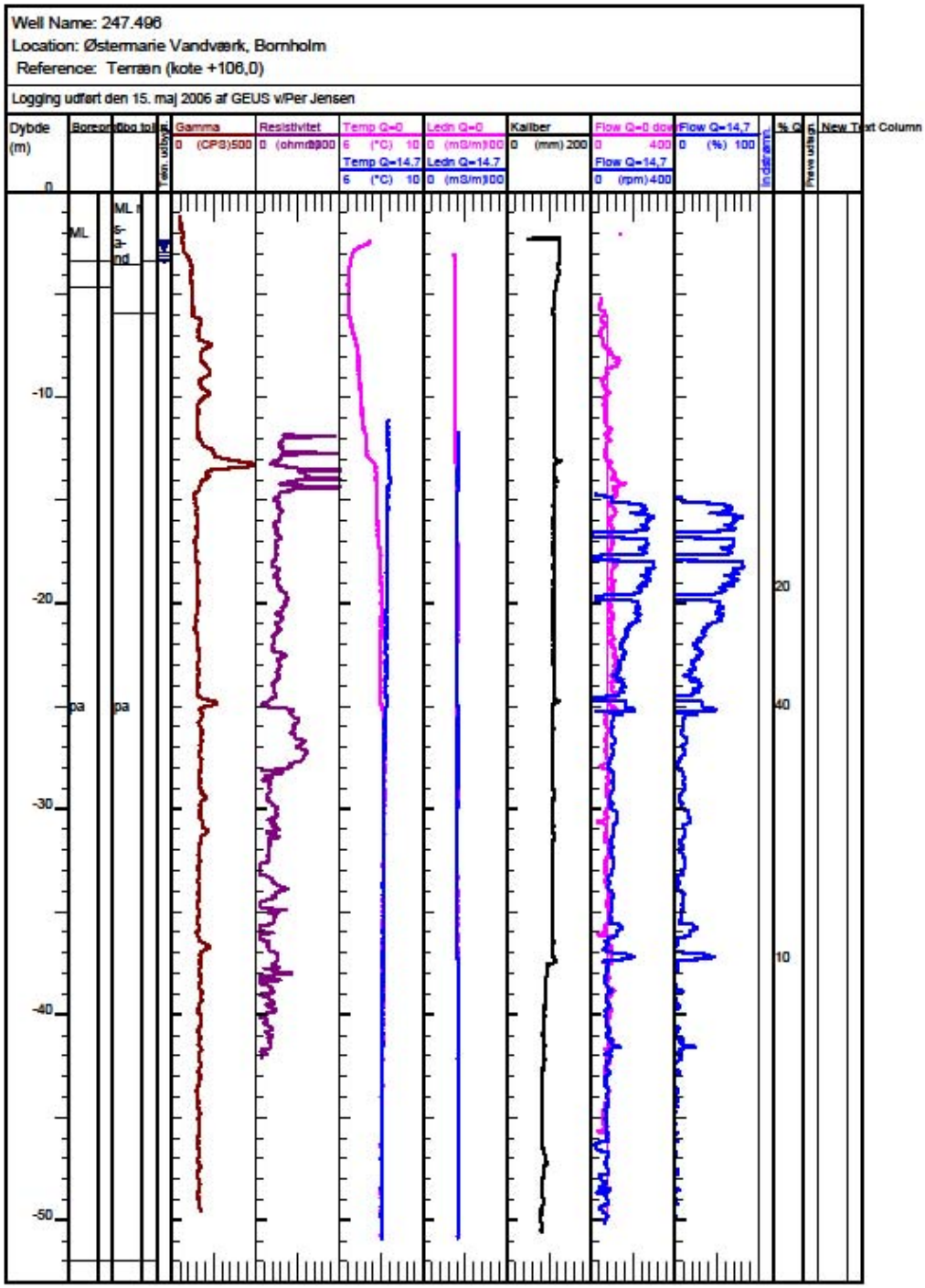

Figure 27. Logs from borehole 247.496, Østermarie Water Work. The Flow log shows the inflow zones in the gneiss (From GEUS Jupiter database).

5.8.2 Drinking water areas

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

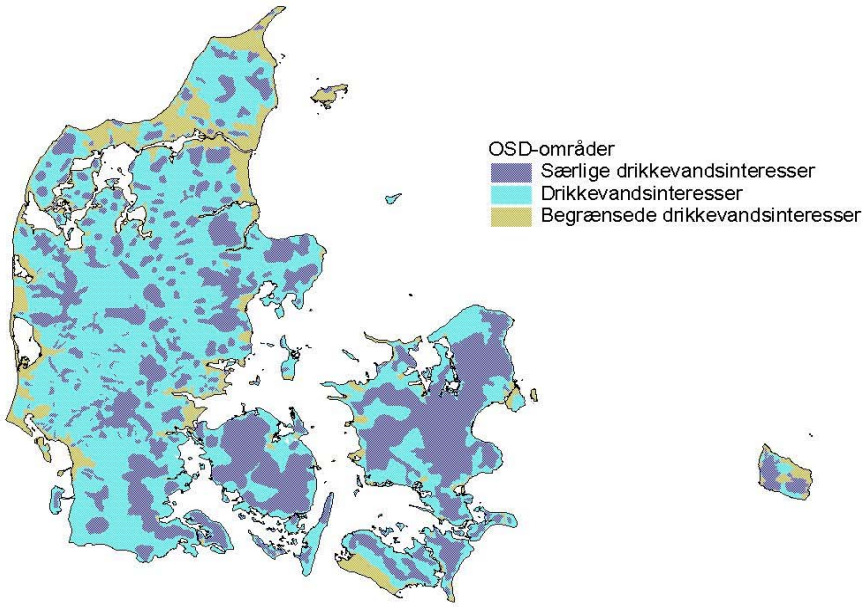

Figure 28. Map of three categories of drinking water interests in Denmark. The areas of special recharge groundwater and drinking water interests (OSD areas, protected by law) are in dark blue colour. The areas shown with light blue colour are areas of some interest for drinking water purposes. The areas in olive brown colour are areas of limited (or none) drinking water interests.

As part of the government´s efforts to protect groundwater, the Environmental Centres have designated areas where major groundwater aquifers exist. The areas are named OSD-areas: "Areas of special drinking water interests" (Fig. 28).

The geographical distribution of the drinking water areas at Bornholm is given in Fig. 29. As shown, Area 1 is located outside areas with the OD or OSD status. In Fig. 30 the recharge areas of Bornholm are shown.

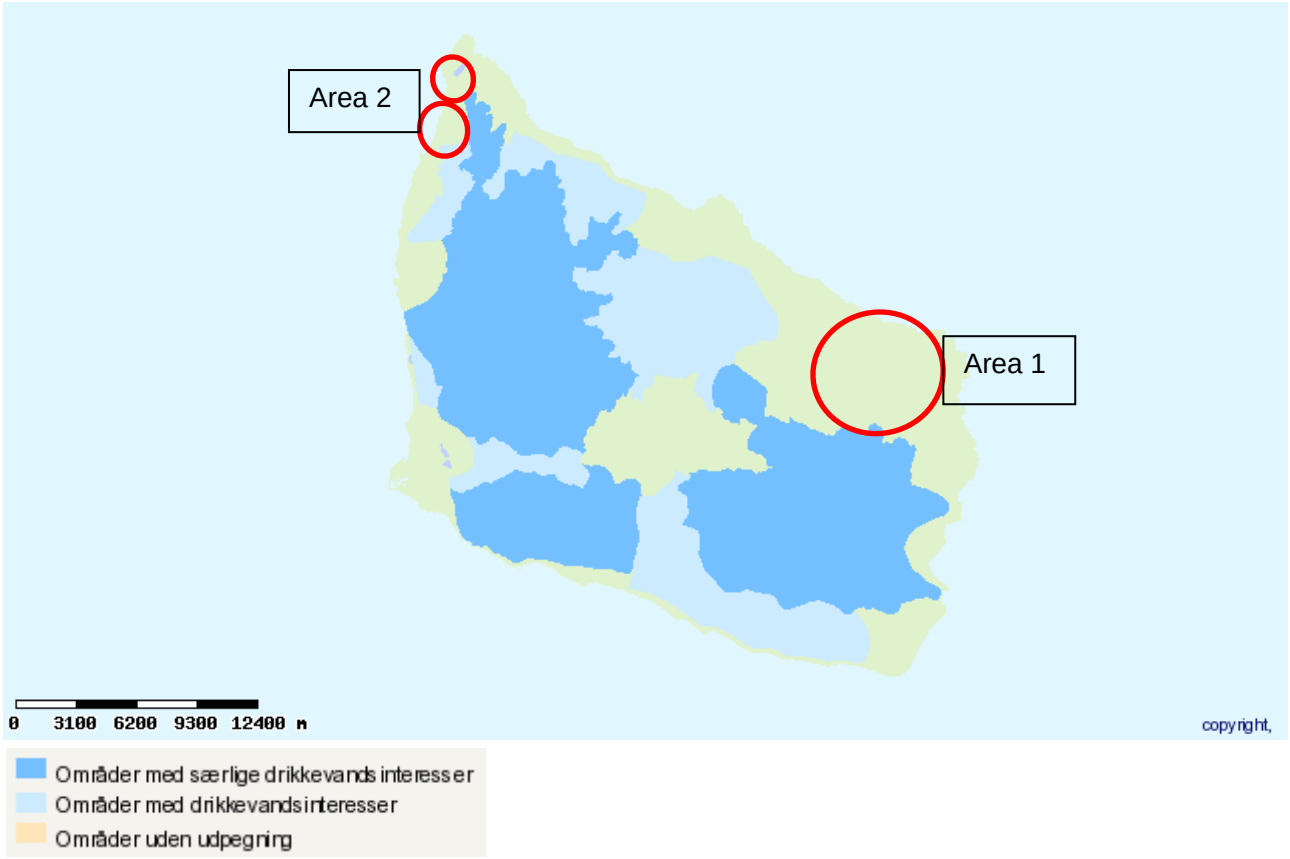

Figure 29. Distribution of the drinking water areas on Bornholm and location of the suggested Area 1 and 2. Dark Blue: Areas of special drinking water interests (OSD); Light blue: Areas of some drinking water interests (OD); Yellow: Areas with limited or none drinking water interests. (From Ministry of Environment Homepage).

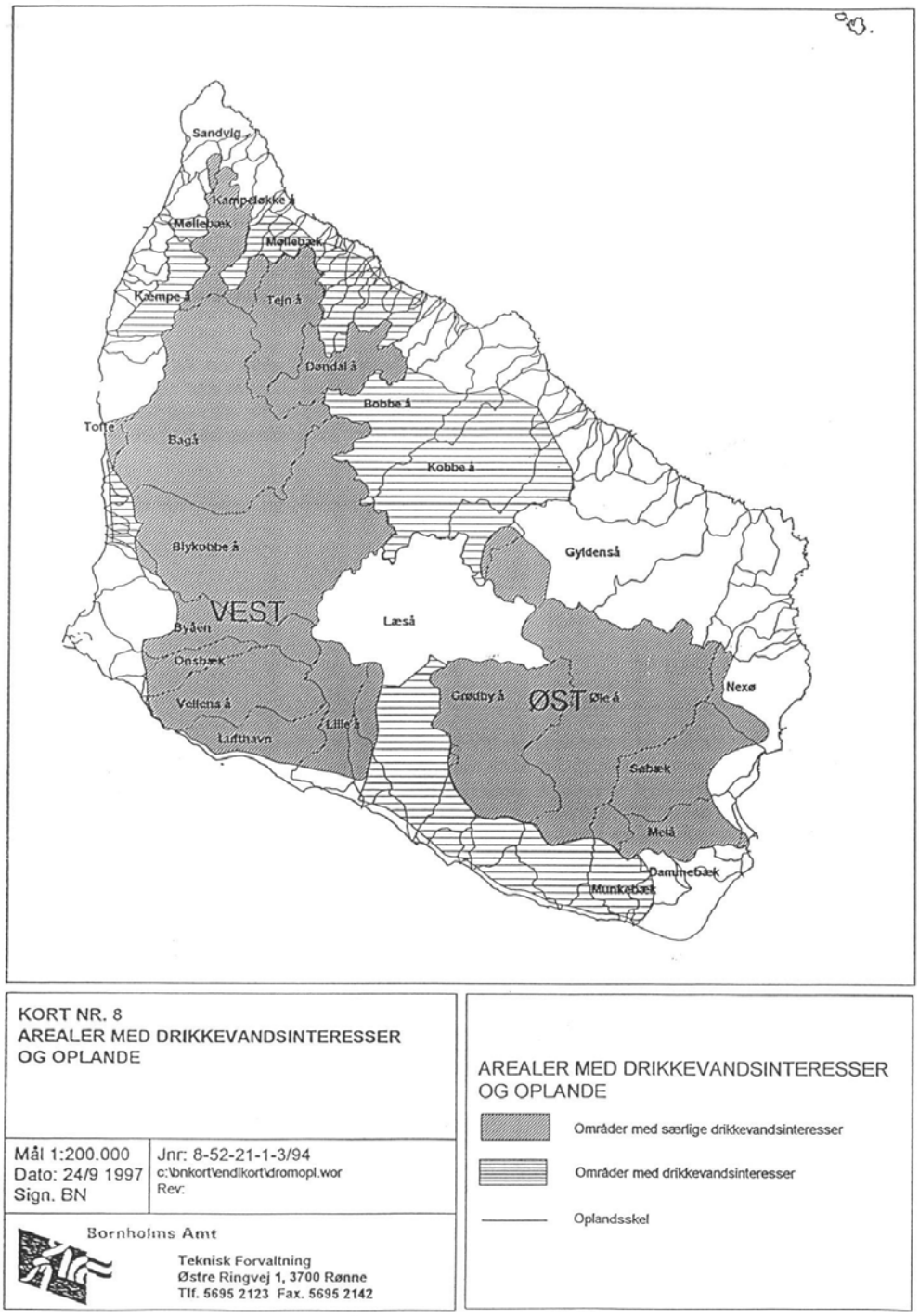

Figure 30. Map of the recharge areas of the streams and brooks. (From Bornholms amt, 1997).

5.9 Groundwater chemistry

The overall groundwater quality aiming for drinking water purpose has been assessed by Bornholm Regionskommune and Environmental Centre Roskilde for the shallow and regional groundwater body and reported in the catchment management plan "Hovedvandopland 3.1, Bornholm". The groundwater chemistry fulfils the EU criteria to be of good status.

The groundwater is characterized as a calcium – "bicarbonate" type which is reduced and without nitrate. A high content of iron indicate weathered gneiss, while a high content of fluoride is normal for bedrocks. The content of chloride is very low and the conductivity far above the needed value. Excessive CO_2 is very low. The groundwater seems not to have any aggressive component in the known analyses.

The content of Radon in the groundwater on northern Bornholm reaches the highest values in Denmark. Analyses from just outside the area (Østermarie Water Work: 70.9 – 434.3 Bq/l Radon and Listed Water Work: Old values from closed wells: up to 920 – 1100 Bq/l Radon and 049-0.55 Bq/l Radium) show that radon be found in all basement reservoirs. This is because the high radioactive minerals mainly are found in the pegmatites which are formed and cooled in late phase of rocks formation where there have been collecting and concentrating of many radioactive components. Therefore pegmatites and radon can be expected in all areas of the basement.

Very few wells are analyzed for chloride within or nearby Area 1. Østermarie water work situated west of Area 1 has 15 – 20 mg chloride/l, which indicates that there are no concerns regarding saltwater intrusion in Area 1 just north of Paradisbakkerne. However, no chemical data are available in JUPITER on chloride contents in wells along the north coast of Area 1, so it is not based on existing data possible to evaluate the risk for seawater intrusion along the north coast.

5.10 Climate and climate changes

The actual climate and the expected future climate changes and sea level development is described in Gravesen et al. (2010, Rep. No. 2). It is obvious, that more and more intense rain may raise the discharge of the streams, especially in the streams that are located at the foot of the Paradisbakkerne. A sea level rise does not cause any troubles for Area 1. It is unclear if and how more and more intense rain will influence on groundwater level.

5.11 Restrictions and limitations

There are no waterworks in the area but only local abstraction wells for household purposes. The area is classified with limited or none drinking water interests. But an OSD important area of Bornholm is found immediately south of Area 1. Only very limited knowledge exist about the spatial distribution of the fracture network in the bedrock in Area 1 and at Bornholm in general.

Area 1 at East Bornholm is situated just north of the Natura2000 habitat area Paradisbakkerne. In addition; minor habitat areas are located along the north coast and one along the Gyldenså outlet to the Baltic Sea (Fig. 31).

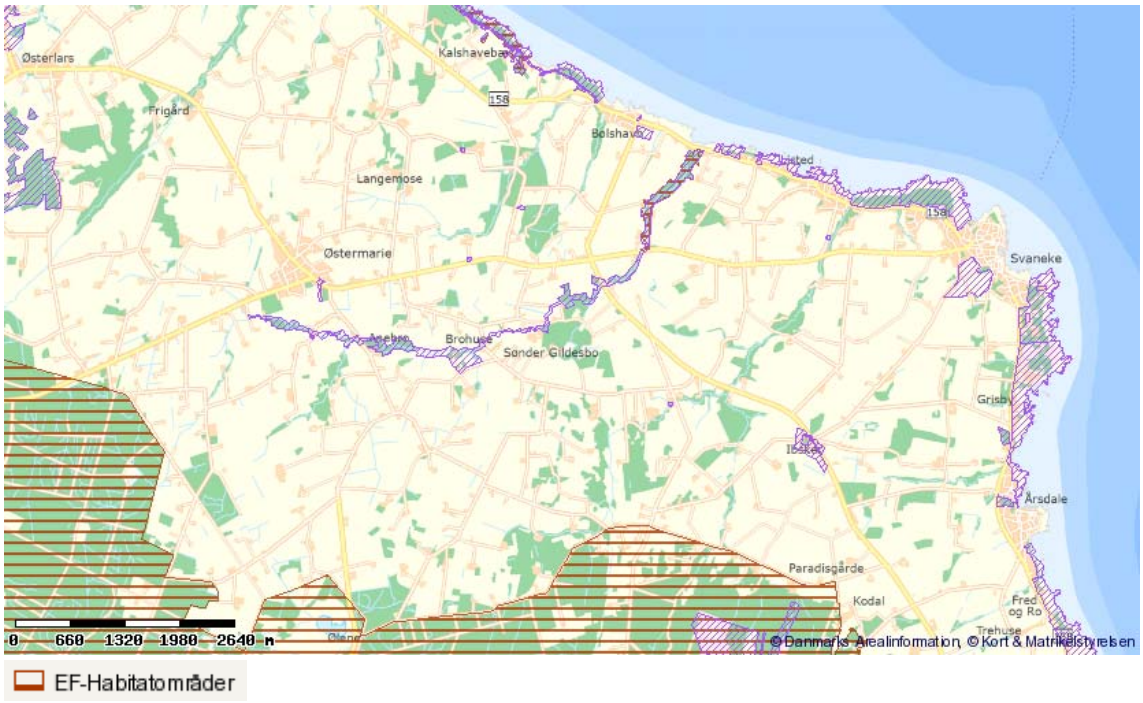

Figure 31. NATURA2000 habitat areas at Eastern Bornholm. (From Ministry of the Environment Homepage) Legend:, Purple hatching: Protected areas.

Other protected areas have only restricted distribution in Area1, and mainly along the coast. Some ancient monuments occur. Areas of National Geological Interests are: Paradisbakkerne, an area around Listed and an area at Årsdale.

5.12 Summary of the area conditions

Amount of data:
Sparse. Some borehole data, nearly none geophysical surveys.

General geology:
The area is part of a relatively uniform and stable basement. Faults and fractures cut the rocks but no data documents the depth, orientation or distribution.

Homogeneous conditions and isolation of the waste by low, permeability layers:
Perhaps perfect on depths below 80 – 100 m but the framework of the fractures below 20 m is unknown. The fracture problem has to be considered as this is the most important problem.

Stability
Good stability on surface and in depth.

Seismic activity and tectonic movements
No seismic and tectonic movements, which can give problems. Minor activity close to Bornholm but the position in the Fenno-Scandian Border zone seems not to introduce activity.

Groundwater conditions
The special groundwater conditions in bedrocks should be suitable but the variation in the groundwater table has to be analysed if the disposal has to be established under saturated conditions.

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

Drinking water interests
No OSD or OD areas are located within the Area 1. Only minor local supplies occur.

Groundwater chemistry, non- aggressive components
The groundwater contains apparently no aggressive components.

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

Climate extreme conditions
Climate changes and extremes as heavy precipitation and storms will not have influence on a disposal.

Other restrictions
It is not expected that any other restrictions will cause problems or limitations.

5.13 Final remarks

The information on Area 1 is mainly recorded from the rim of the area in two quarries in Paradisbakkerne supported by some boreholes. The outcrops demonstrate the structural framework of vertical, inclined and horizontal fractures and joints down to 12 m below ground surface. Some boreholes show fractures at larger depth. Area 1 is situates in a lower terrain than the Paradisbakkerne and the basement rocks are covered by a thin Quaternary cover.

In Sweden and Finland low – and intermediate level waste disposals are located in Precambrian basement rocks. At Forsmark in Sweden, the low and intermediate waste is placed in tunnels and caverns in the rocks 50 m below the sea bed surface within other shielding (see photo page 80). The storage chambers consist of four 160 m long caverns and a 70 m high cavern with a silo. The Finnish caverns are situated 100 m below ground surface. The Swedish basement rocks also suffer of fractures to large depth but still, the conditions in the area have pointed this disposal site solution.

The two areas on Bornholm give different possibilities: A construction from the ground surface or from the bottom of granite quarries.

6. Area 2. Granite Quarries, Vang- Hammeren, North West and North Bornholm

6.1 The location of the area

This area on northern Bornholm consists of 5 quarries, which makes it rather special compared to the other areas (Figs. 32 and 33). It is geographically separated into two subareas. The reason for pointing out the quarries is the possibilities for construction of a waste disposal in the bottom or side of the quarries as e.g. caverns.

a. On Hammeren, the old, large Hammeren Quarry is located on the southeast part of Hammeren. The lowermost part of the quarry is filled by (rain) water and called Opalsøen. On the top of Hammeren, the smaller Stejlebjerg Quarry is found. The lower parts are filled by rainwater and are called Krystalsøerne. The area has boundaries to the Baltic Sea, the Hammer Sø towards the southeast and the valley between Sæne Bugt and Osand Bugt. The highest point is approx. 60 m above sea level.

b. In the Vang area, tree quarries are found: One old quarry south of Vang Harbour which is open towards the sea and two quarries in the Ringebakker: the Vang Quarry towards the north including a small older quarry, and the Almeløkke Quarry towards the south. The area is limited by the Baltic Sea towards west, the Vang town towards north, the valley Ringedalen towards the east and the Blåskins valley towards the south.

Figure 32. Location of the area. Bornholm is located in the Baltic Sea east of the mainland Danmark.

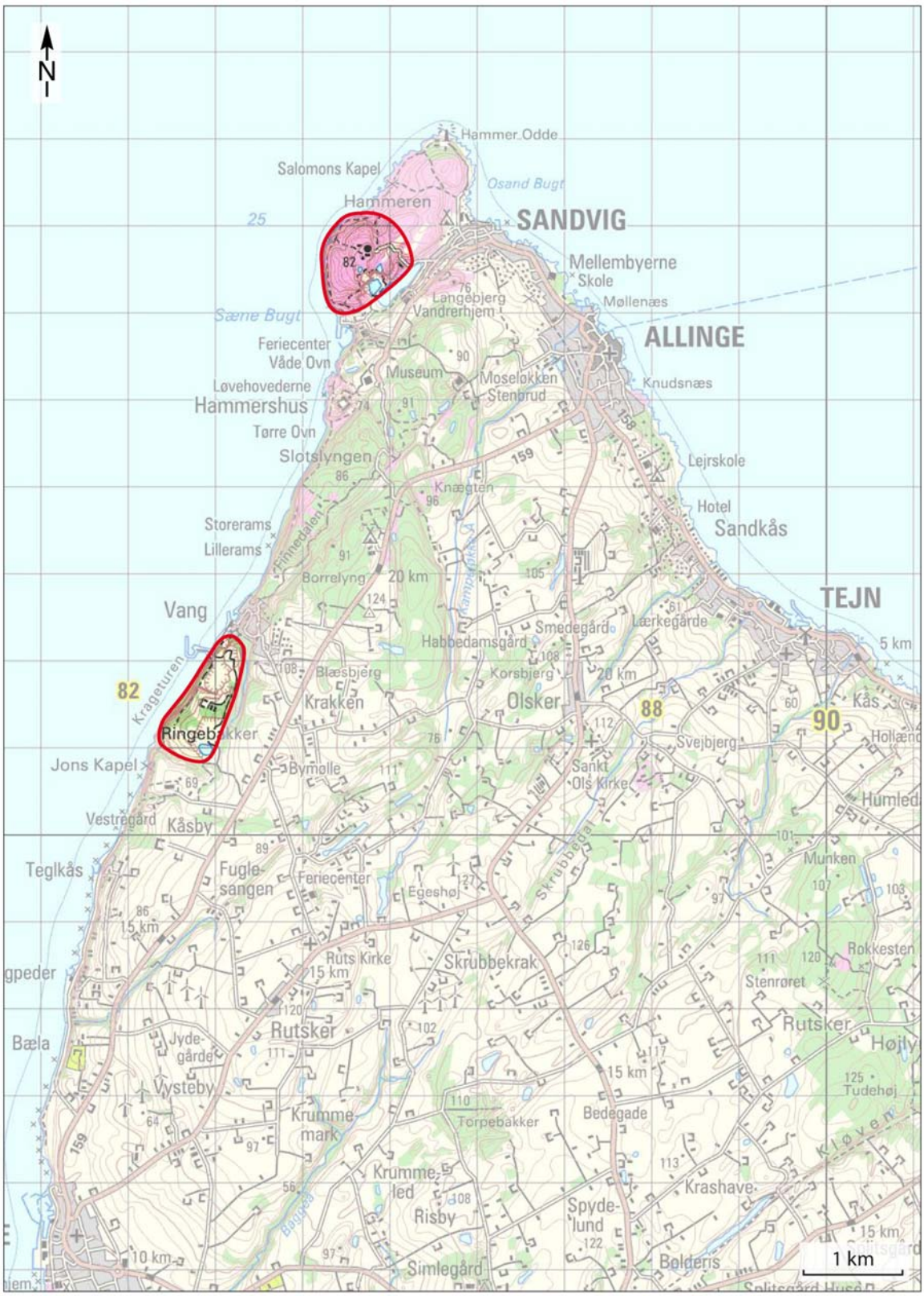

Figure 33. A detailed map of Area 2. The area is located on the northern and north western part of Bornholm.

6.2 Terrain, topography and processes

6.2.1 Area 2a, Hammeren

The area is located on the south-western part of the Hammeren, which is the largest rock moutonnée on Bornholm. The size of the Area 2a is c. 0.73 km^2. Most of the area is included in one big, almost dome-shaped group of rocks. The top-level is 82 meters above sea-level, which is found next to the lighthouse and on the top of the "hill" "Kælderbakke". From the top/central part of the area, the terrain is dipping toward the periphery. The steepest gradients are found toward NE, along the fracture valley "Sandhammeren" and in the N-, W- and South-westerly directions toward the coast. Toward the SE, the area is bounded by almost vertical, artificial made cliffs along the old quarry. The area includes no streams or lakes, except for (rain water) lakes in the old quarries.

A small road leads to the lighthouse and a track/path runs along and close to the coast. The area is partly covered by heather and birch, oaks and Scotch pine. Except for the lighthouse, a parking place and a house for the lighthouse keeper, the area appears in a state of nature.

Surface processes of a rocky landscape like this are few and slowly proceeding and primarily connected to frost–thaw-processes.

Area 2b, Vang

The area is located on the north-western part of Bornholm. The size of the Area 2b is c. 0.93 km^2. Most of the area is included in one big elongated group of rocks oriented parallel to the coastline. The top-level is c. 90 meters above sea-level. From the top/elongated central part of the area, the terrain is dipping toward the periphery. The steepest gradients are found toward the coast.

A few small roads lead to the harbor and some houses in the central part of the area and a track/path runs along and close to the coast. The quarries make up c. 25 % of the area. The remaining part of the area is almost equally used for agriculture and woods. The area includes no streams or lakes, except for a (rain water) lake in one of the old quarries.

Surface processes of a rocky landscape like this are few and slowly proceeding and primarily connected to frost–thaw-processes.

6.3 Surface geology and profiles

Most of the surface is covered by a relatively thin cover of clayey and sandy tills but the Precambrian rocks are often exposed directly on the surface (Fig. 34). Many good profiles in the Precambrian rocks are available in the quarries (Figs. 35 and 36). The Quaternary sediments are more difficult to observe.

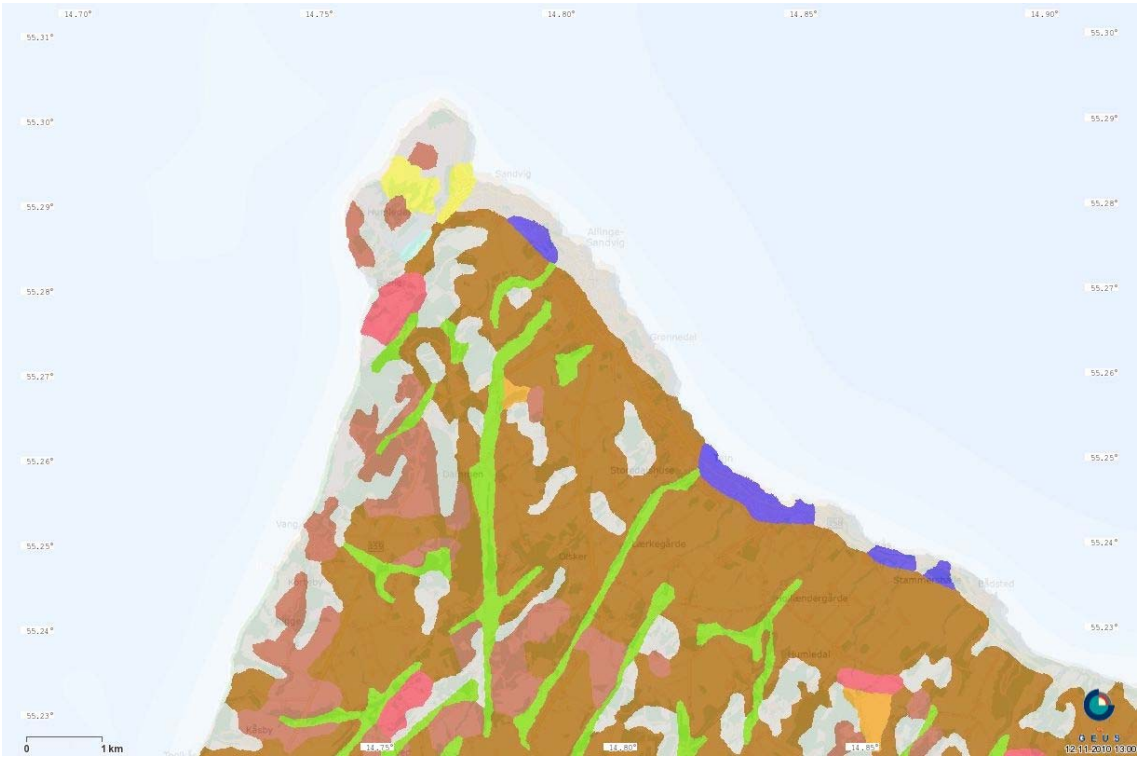

Fig.34. Map of the Quaternary deposits (From GEUS Homepage after Pedersen, 1989). Legend: Brown: Clayey till, Red Brown: Sandy till, Red: Meltwater sand and gravel, Blue: Late Weichselian marine deposits, Green: Holocene Freshwater deposits, White: Precambrian basement.

Figure 35. Orthophoto of the Hammeren area (Area 2a) showing the Hammeren Quarry and Opalsøen (Form GEUS Homepage after KMS).

Figure 36. Orthophoto of the Vang area (Area 2b) with the old quarry at coast, the Vang Quarry close to the harbour and the Almeløkke Quarry towards the south (From GEUS Homepage after KMS).

6.4 Boreholes

The area is only covered by very few boreholes (Fig. 37). In the Hammeren area only four boreholes are found and in the Vang area also four boreholes occur (raw material boreholes). A borehole log is seen in Fig. 38.

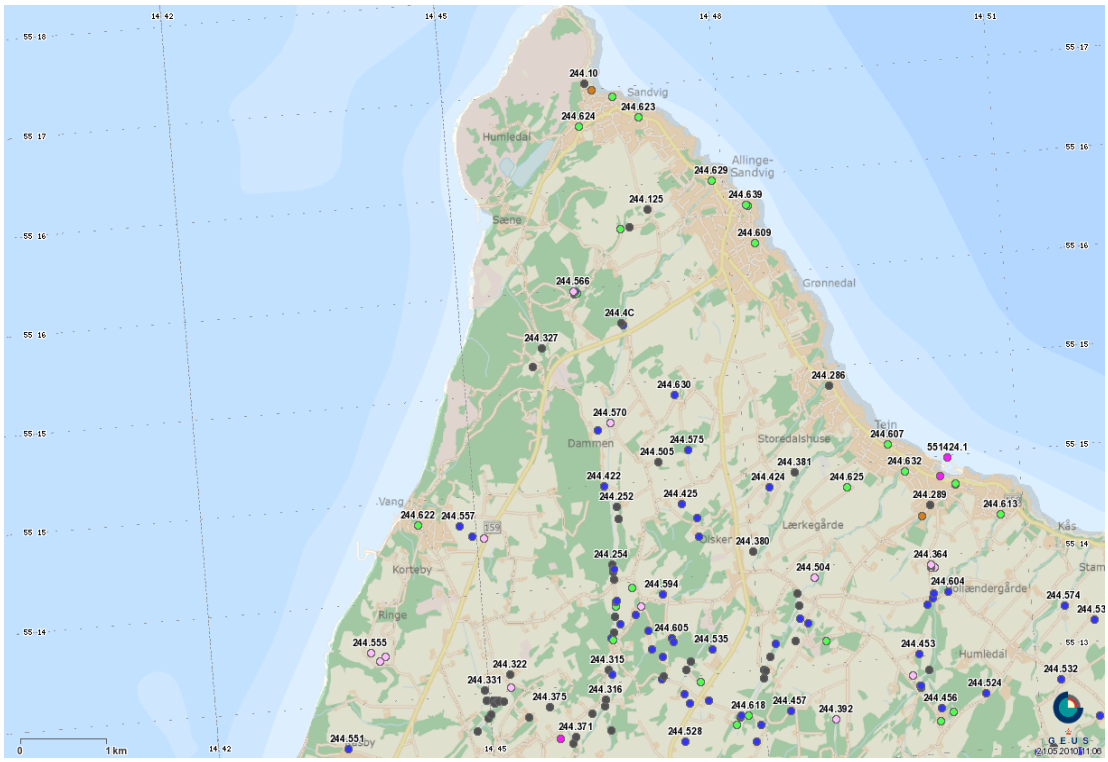

Figure 5. Location of boreholes in the area. (From GEUS Jupiter Well Database). Legend: 247.344: Database archive no., Blue dots: Water supply wells, Black dots: Unknown purpose, Green dots: Other Boreholes, Pink dots: Raw material boreholes, Light red dots: abandoned boreholes, Orange dots: Geotechnical boreholes.

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Udskrevet 6/9 2010 Side 1

BORERAPPORT

DGU arkivnr: 244. 554

Borested : Ringdalsvej, (Bukkegård), Vang Granit
3790 Hasle
Borehul 1

Kommune : Bornholm
Region : Hovedstaden

Boringsdato : 1/12 1993

Boringsdybde : 60 meter

Terrænkote : 63.62 meter o. DNN

Brøndborer : Se notatfelt
MOB-nr :
BB-journr :
BB-bornr : 1

Prøver
- modtaget :
- beskrevet :
- antal gemt : 0

Formål : Råstofboring
Anvendelse : Sløjfet/opgivet bor
Boremetode : Kerneboring

Kortblad : 1812 IVNV
UTM-zone : 33
UTM-koord. : 482945, 6121073

Datum : ED50
Koordinatkilde :
Koordinatmetode : KMS digitale kort

Notater : Brøndborer:Kernboring AB

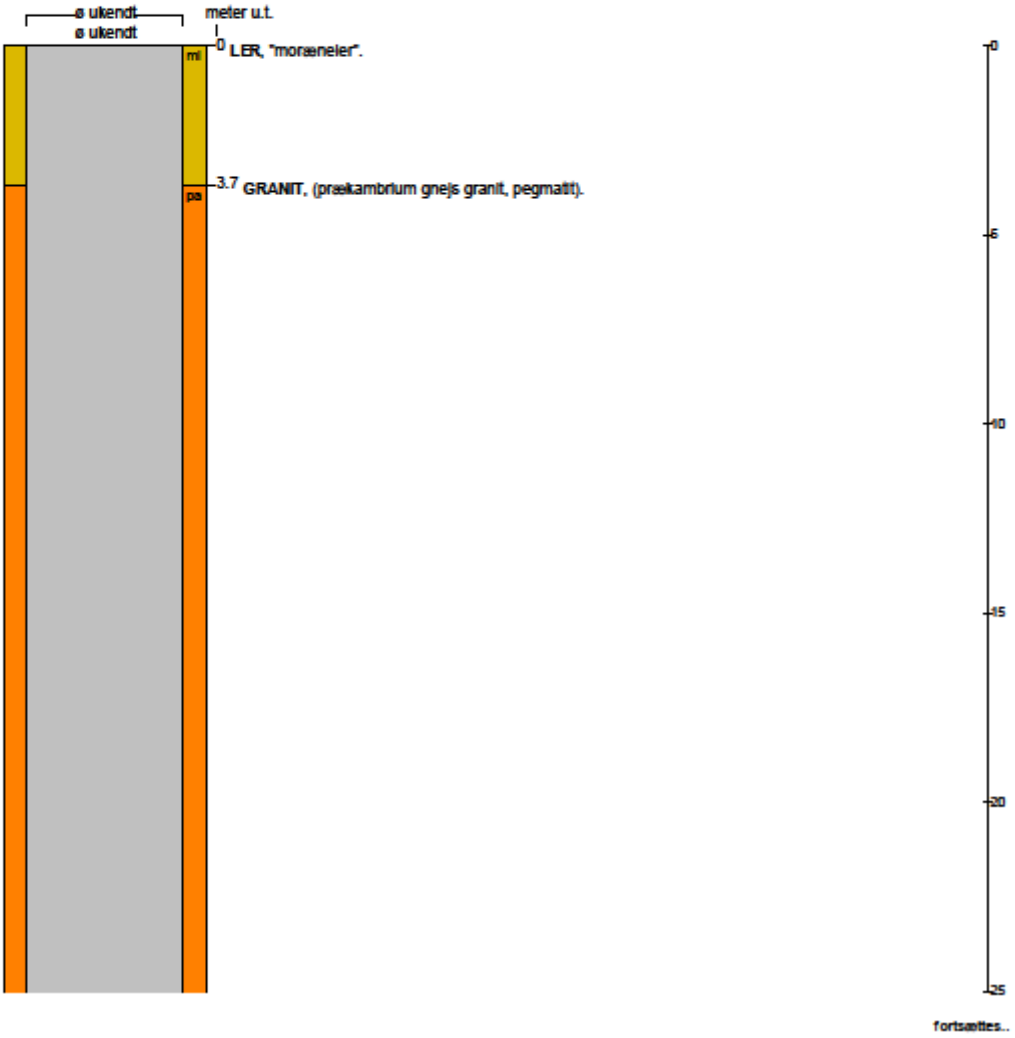


Figure 38. Geological log from the borehole DGU NO. 244.554: Upper part of the 60 m deep raw material borehole. (From the GEUS Jupiter database).

6.5 Sediment and rock characteristics, mineralogy and chemistry

6.5.1 Pre-Quaternary rocks

Hammer Granite

Mineralogy
The area consists of two different intrusive granites which probably belong to the youngest basements rocks on Bornholm: Hammer Granite and Vang Granite. As The Hammer Granite cuts and sends apophysis into the Vang Granite, the former is the youngest. The boundary of the Vang Granite to the gneiss occurs at the coast south of Vang Harbour.

The Hammer Granite is a light grey-red, fine to medium-grained rock with characteristic small red dots of hematite which is coating on individual grains (Fig. 39). The granite contains bodies of coarse-grained pegmatites and fine-grained aplites. The mineralogy is: quartz 33 %, perhite 41 %, plagioclase 18 %, hornblende 1 %, biotite 4 %, titanite 1 %, ore 2 %, and traces of apatite, epidote and fluorite. In the feldspar and quarts rich pegmatites occurs the radioactive mineral gadolinite.

Weathering
The weathering of the Hammer Granite is often related to fracture zones. On Fig. 39 four different stages of a weathering process can be seen and in Fig. 40 a strongly weathered vertical fracture zone occurs. The iron minerals are oxidised to yellow brown ochre and the rocks are altered to white kaolin. Black manganese oxide is formed in the fractures.

The Area 2a Hammeren only consists of Hammer Granite.

Figure 39. Fine-grained Hammer Granite. The four smaller fragments represent different levels in the weathering process of the granite: One fragment with yellow brown weathering of iron oxides, two grey and white fragments in different degree of kaolin weathering and one black fragments of manganese oxide formed in a fracture.

Figure 40. Strongly fractured Hammer Granit with yellow brown weathered fracture zones. Hammeren Granite Quarry.

Vang Granite

Mineralogy

The Vang Granite is a medium-grained grey-red granite with many spots of dark minerals (Fig. 41). It is often weakly foliated with c. 45^{o} dip towards the north. The foliation increases towards the south. South of the Almeløkke Quarry is a gradual boundary to the Bornholm Gneiss, which occur below the Vang Granite. North of Vang Harbour, the contact to the Hammer Granite is a weakly dipping slice under the Vang Granite. The granite contains many inclusions of older rocks and veins and dykes of pegmatites and aplites.

The granite consists of: quartz 27 %, perthite 33 %, plagioclase 22 %, hornblende 5 %, biotite 6 %, titanite 1 %, ore 3 % and with traces of fluorite.

The light minerals are myrmekittic grown which gives the rock a cohesive force and ductility.

The pegmatites and aplites consisting of quartz and perthite are often found, while diabases are rare in the quarries.

Weathering

The granite is strongly weathered in some of the fracture zones. The yellow brown colour indicates weathering of minerals with iron content. The plagioclase, weathered to sericite and chlorite is also found in the fractures (Fig. 42).

The Area 2b only consists of Vang Granite.

Figure 41. The red grey medium-grained Vang Granite from the Vang Quarry.

Figure 42. The Vang Quarry: Fracture zones in the Vang Granite with yellow brown coloured strongly weathered parts.

6.5.2 Quaternary deposits

The Quaternary cover in the areas around the quarries is very thin (Figs. 34 and 43). On the Hammeren, thin layers of clayey till and aeolian sand deposits occur but most of the area is without cover. In the fracture valley from Sæne Bugt to Osand Bugt is found meltwater sand and gravel. The Vang area is partly covered by clayey till and partly without cover. An investigation southwest of the Almeløkke Quarry on Bukkegård fields shows a clayey till cover. The thickness is between zero and 10 m.

During the Quaternary time, the northwestern part of Bornholm was exposed to erosion during the various ice advances through the Baltic. The cliff surfaces have the characteristic morphology of glaciated basement rock, the rock moutonnée. Related to these morphological features, a number of glaciotectonic fractures were implemented down into the basement rock in the subsurface. Here, they occur down to a depth of more than 30 m. The fractures are sub-horizontal with a spacing of about 1 m (Figs. 42, 45 and 46). A few areas with glaciofluvial deposits have been preserved and a sandy till of varying thickness covers the basement rocks in random distributed patches.

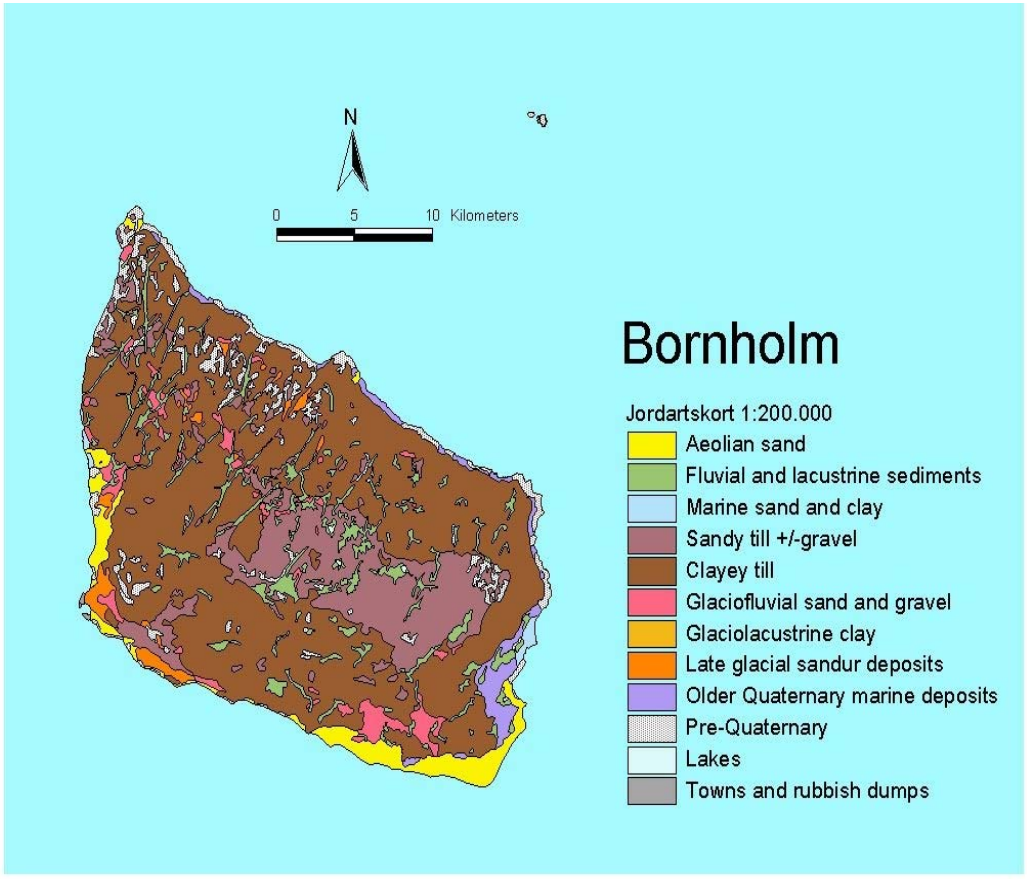


Figure 43. Map of the Quaternary surface deposits (After Pedersen, 1989).

6.6 Tectonics, structures and seismic activity

6.6.1 Major tectonic structures

The Hammeren area is bounded towards the southeast by a large rectilinear fracture valley with a NE-SW orientation, the same orientation as the other large valleys originated as fracture – fault zones. The Hammeren is a rounded and eroded rock moutonnée formed by the Quaternary glaciers coming from the northeast. It is crossed by at least two fracture zones with the same directions and by three zones with more N-S and NW-SE directions.

The Vang area is bounded by large fracture valley zones NE-SW and NW-SE. The granite is cut by fractures with NW-SE directions often in zones with very small spacing.
The Vang Granite is cut by diabase dykes and sandstone dykes.

The fracture zones on Hammeren and Vang are considered as large Precambrian fault zones with mainly the same directions as many other fault zones on Bornholm (Figs. 16 and 44).

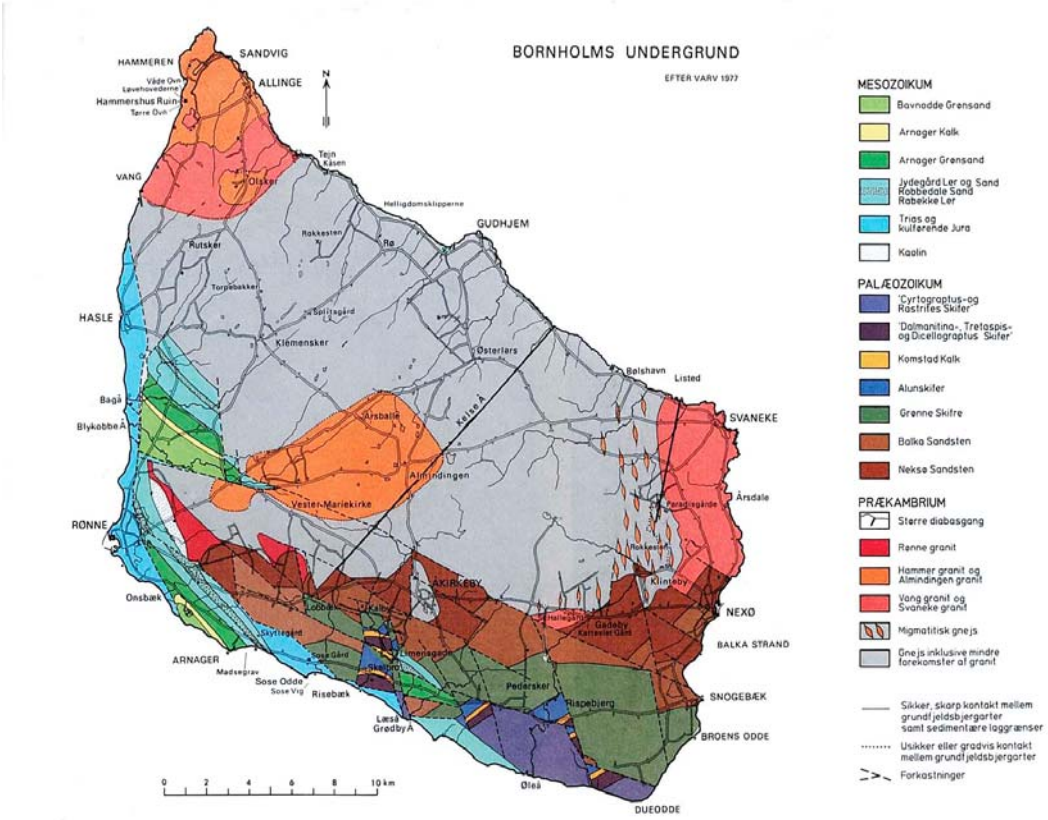


Figure 44. Map of the Pre-Quaternary surface which shows the older rocks and sediments below the Quaternary sediments. Some major fault lines and diabase dikes are also shown. (From Varv, 1977). Legend: Prækambrium: Precambrian (grey and red colours), Palæozoikum: Palaeozoic, Mesozoikum: Mesozoic. Various major rock and sediment units are shown by different colours.

6.6.2 Fractures

Hammer Granite

The fractures in the Hammer Granites have been investigated and measured for many years. The granite is cut by several pronounced fracture systems with orientations N-S, NE-SW and NV-SE. The vertical spacing is between few cm and 2–3 m. The horizontal spacing can be up to several meters and is probably increasing downwards (?) (Fig. 45). As a consequence of the many vertical and horizontal fractures, the rock can have a blocky structure (Fig. 45).

Figure 45. Hammer Granite, Hammeren Quarry. The granite is cut by many fractures.

Figure 46. Vang Granite, Almeløkke Quarry. The granite is cut by inclined fractures.

Vang Granit

The local fracture pattern in the Vang Quarry is mainly WNW-ESE and the spacing varies from a few metres to few cm in up to 15 m broad fracture zones. The granite is often strongly weathered in these zones.

The pattern in the Almeløkke Quarry is a dominant ESE-WNW direction of steep fractures but in some part of the quarry the directions are NNE-SSW, NE-SW or NNW-SSE. Some of the fractures are inclined 45^{o} towards NE (Fig. 46). The spacing seems to be larger here than in the Vang Quarry.

Core samples from three boreholes demonstrate that fractures, shear zones and weathered granite occur down to 60 m below the surface (Fig. 47). Examples of sandstone filled fractures oriented WNW-ESE are also found in the Vang Granite.

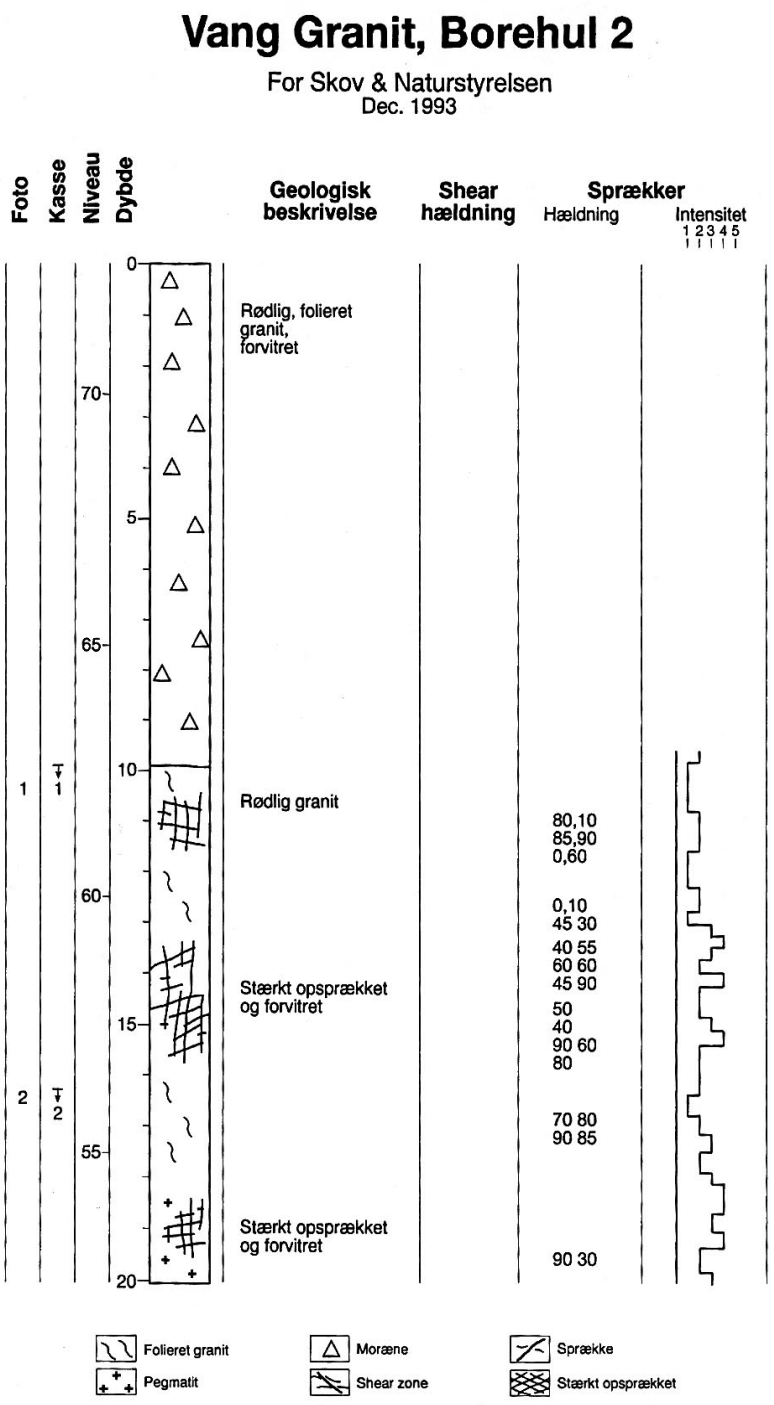
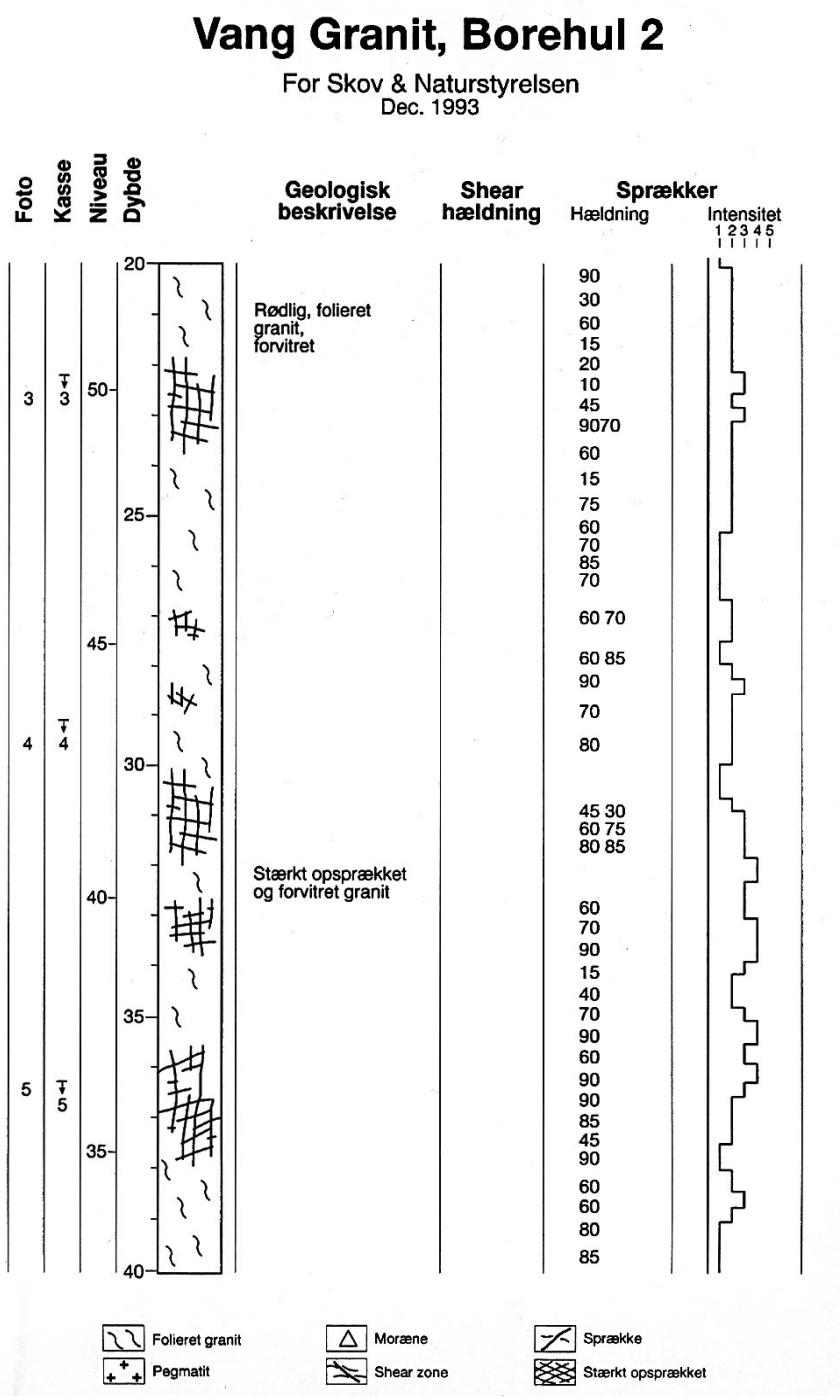


Figure 47. Geological log of the raw material borehole DGU no. 244.555 drilled into the Vang Granite. The Core samples demonstrate fractures and shearing down to 60 m below ground surface (From Knudsen, 1994).



Fig, 47. Continued.

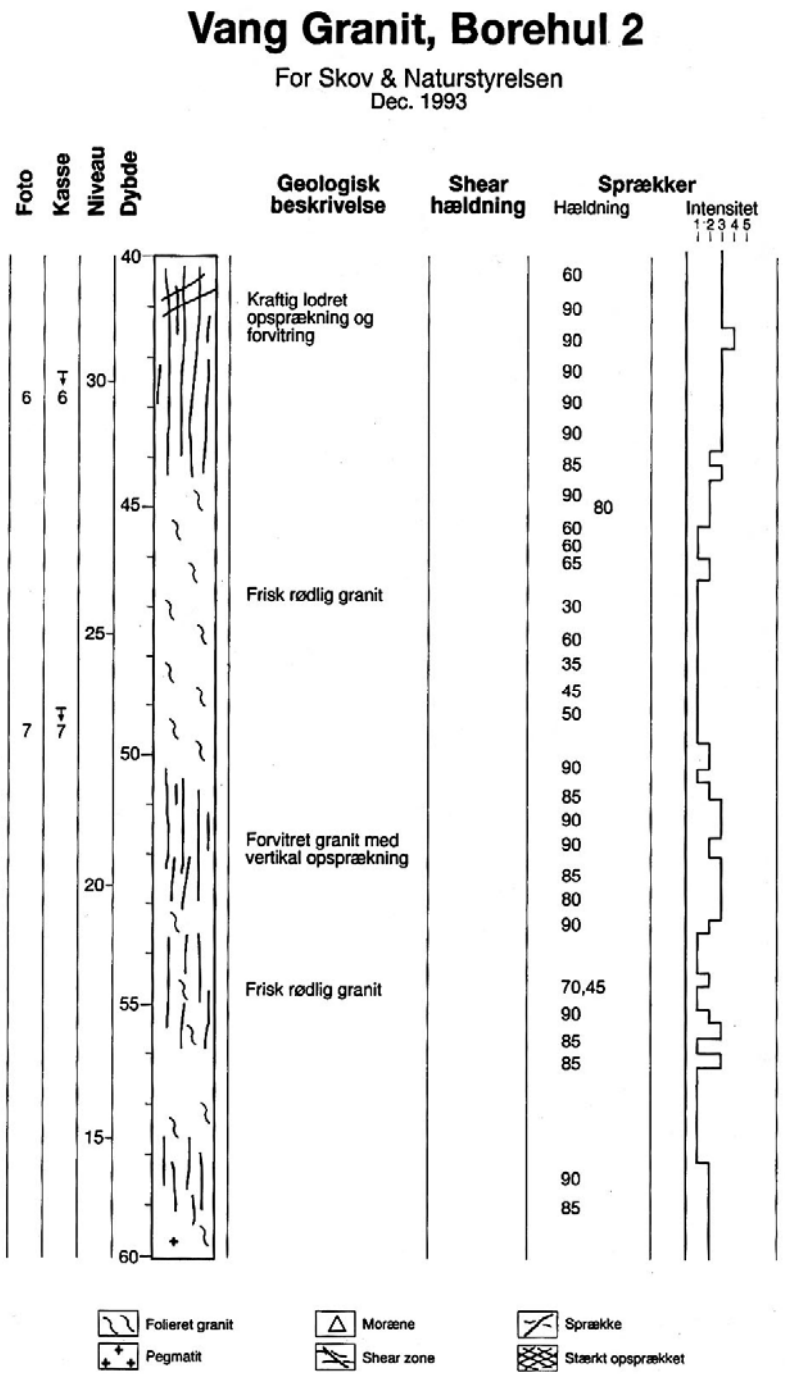


Figure 47. Continued.

The granites and gneisses have no primary porosity in the “matrix” and the porosity is only related to the secondary fractures (macro pores). These characteristics are very important for the water transport and the water supply.

6.6.3 Geological and structural models

The geological model for the Hammer Granite in the Hammeren Quarry area is:

A. Quaternary cover of thin till deposits

B. Hammer Granite

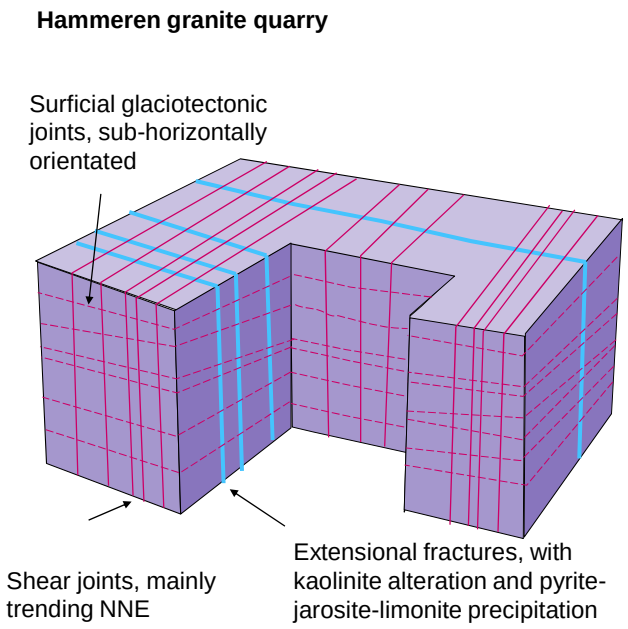


Figure 48. Geological and structural model for the Hammer Granite.

The more detailed structural model of the granite is (Fig. 48):

The structural geology of the basement rocks in the NW corner of Bornholm is dominated by planar, vertical jointing related to the pre-Quaternary geological development, and sub-horizontal to moderately northerly inclined fractures formed during the glaciation of Bornholm during late Pleistocene. At Hammeren, the pre-Quaternary fractures constitute compressional shear joints trending SSE–NNW and extensional fractures trending ENE–WSW. In the extensional fractures, kaolinite alteration affected the brecciated granite kata-clasts (Fig. 48). Moreover, rusty brown iron-hydroxides and black manganese oxides have been precipitated in voids, scattered distributed in the exten-

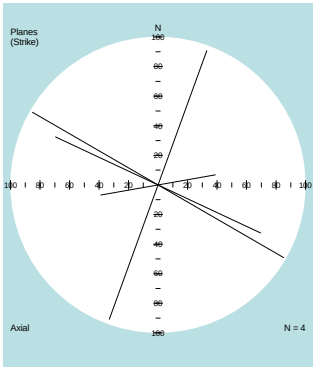
sional fractures (Figs. 39 and 40). The jointing systems are strongly reflected in the geomorphology at Hammeren, where the main vertical fractures surfaces form the characteristic tacked coastal morphology, and the extensional fracture orientation parallel the elongation of the Hammer Sø, the lake separating the rocky landscape Hammeren from the mainland of Bornholm.

The simple geological model for the Vang Granite in the Vang Quarries and the Almeløkke Quarry is:

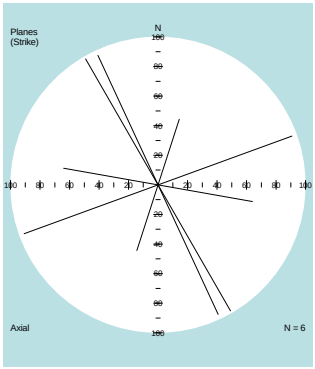
A1. Quaternary cover with thin till deposits

B1. Vang Granite

The more detailed structural models for granite at the two quarries follow below (Fig. 49, 50 and 51):



Main joint orientation in Vang granite quarry.
Long line indicate vertical joint, shorter line
magnitude of dip between 90 and 0°.



Main joint orientation in Almeløkke granite quarry.
Note the dip of 35° and 50° of inclined, conjugate joints

Figure 49. The main directions of the joints in the Vang Granite, Vang and Almeløkke Quarries.

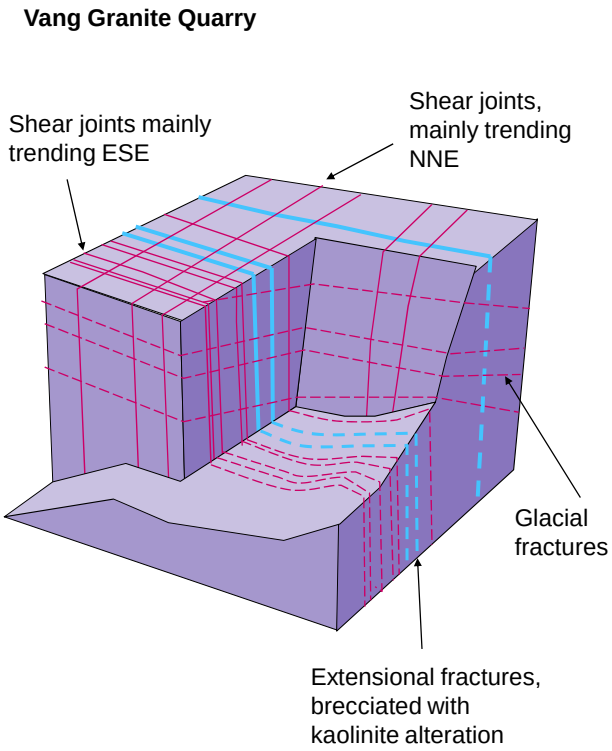


Figure 50. Fractures and joints in the Vang Granite, Vang Granite Quarry.

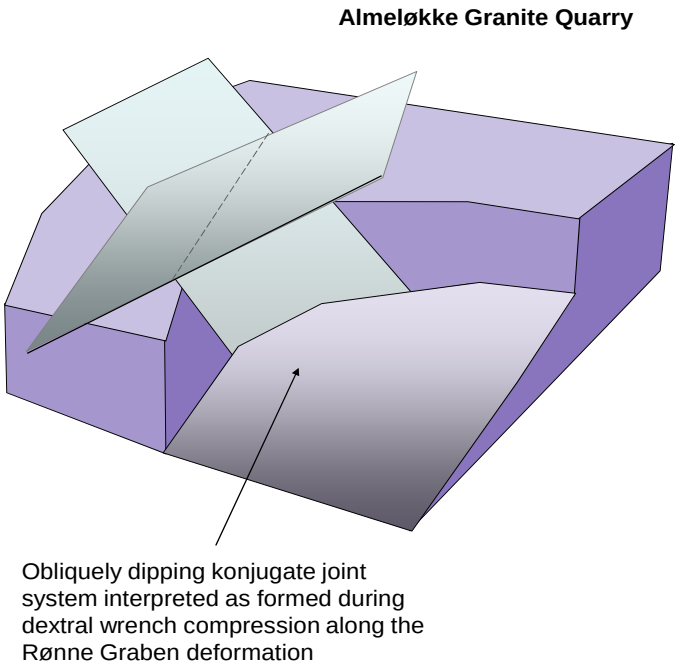


Figure 51. Geological and structural model for the Vang Granite in Almeløkke Quarry.

Along the west coast - about 5 km south of Hammeren - the old granite quarry at Vang is situated, which is considered due to its obvious constructional facilities. The Vang Granite is reasonable dense, medium-grained granite (Fig. 41). However, the granite rock at the quarry is heavily fractured by the conjugate, shear fractures orientated perpendicular to each other in the directions trending NNE and ESE. The latter of these fractures systems (ESE) has a fracture density of 3 vertical joints per running meter in a cross section perpendicular to strike (Figs. 49 and 50). Some of these fractures developed into extensional fractures with kaolinite altered breccias. The shear fractures in Vang as well as at Hammeren are interpreted to have formed during the main dextral trans-pression in the Tornquist-Sorgenfrei Wrench-Fault Zone.

The Almeløkke granite quarry ca. 5 km south of Vang is another prosperous location, which has been investigated. Here, the vertical shear joints recognized in the Vang Granite quarry occur as well, but a very strong obliquely orientated conjugating joint system superimpose the vertical joints (Fig. 49, 50). This system is interpreted as formed during the inversion tectonic related to the eastern boundary of the Rønne Graben. The subhorizontal fractures in both quarries have been formed by Quaternary glaciers mainly coming from east and northeast.

6.6.4 Earthquakes - seismic activity

The seismic activity in the Bornholm area, the island and the near surrounding sea, is very low (Fig. 52). Almost no seismic movements have been registered on Bornholm although a seismic station is located in Almindingen.

Therefore, it is impossible to relate recent seismic activity to the many faults and fractures in the bedrocks and other signs of recent movements along the faults and fractures have not been proven. The island is considered as tectonic stable although it is situated in the Fenno-Scandian Border Zone.

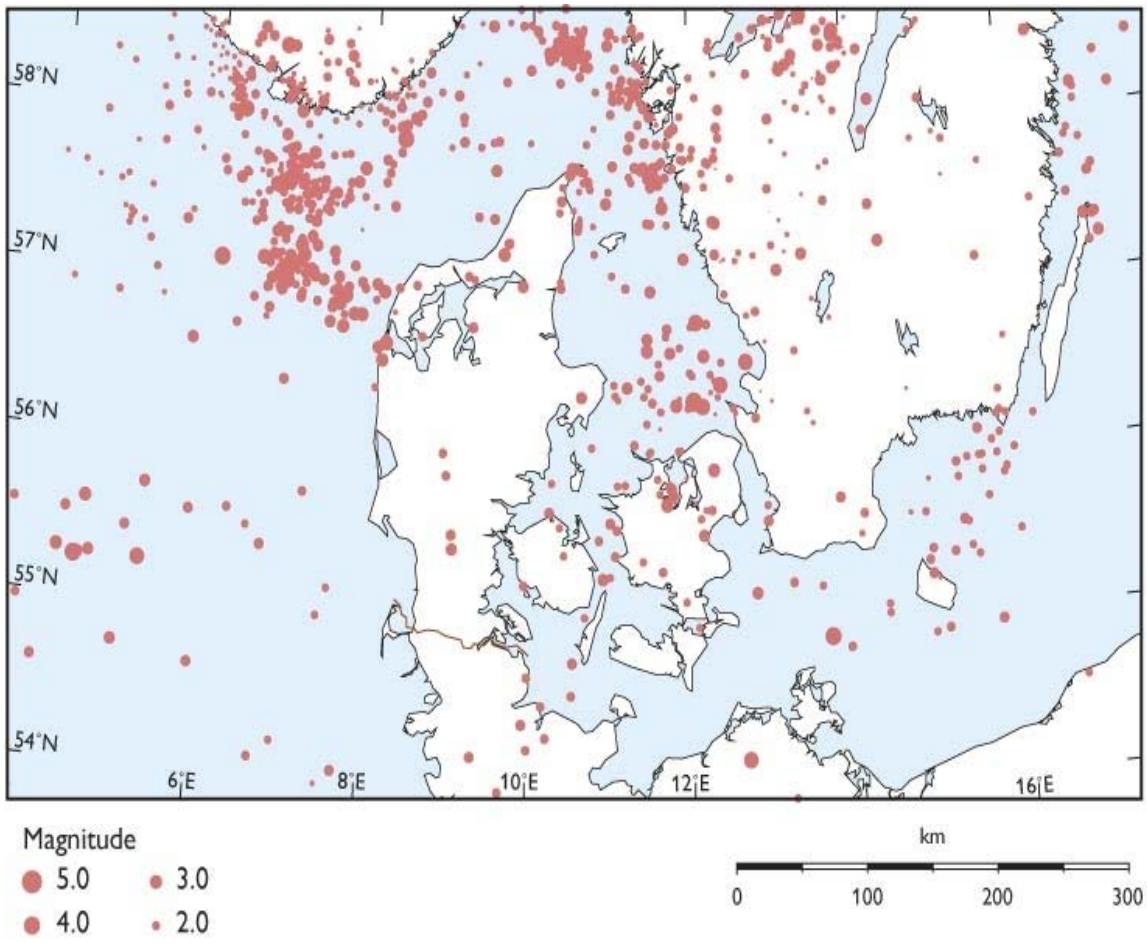


Fig.52. Seismicity in Denmark and the surrounding areas 1970 to 2008. Epicentres are from GEUS earthquake catalogue and Catalogue of earthquakes in Northern Europe by University of Helsinki. All epicentres are determined using a minimum of three stations (After Larsen et al., 2008).

6.7 Ground stability

The ground stability of the area is very good. There are apparently no earthquake disturbances, no deposits of glacial sediments with glaciotectonic structure which could give unstable conditions and no slope where recent sliding of material can occur. Bloc falls may occur in the quarries or along coast escarpments.

6.8 Groundwater hydrogeology

6.8.1 Groundwater characteristics

The Hammeren-Vang sites on northwest Bornholm (Area 2) is located in an area that is characterized by presence of one shallow groundwater body (DK 3.1.1.1) covering the entire Bornholm (Fig. 53) and one regional groundwater body (DK 3.1.2.3), that covers most of the northern part of Bornholm (Fig. 54). There are no deep groundwater bodies identified at the island Bornholm. The shallow groundwater body consists of meltwater sand deposits but the extension of the groundwater body is not very well defined. Based on lithological information from the JUPITER database, is it very likely that DK3.1.1.1 within Area 2 has a very limited extension. The regional groundwater body DK3.1.2.3 consists of fractured basement rock that very likely is covering the entire or most of the suggested Area 2. The subdivision into groundwater aquifers are thoroughly described by the former Bornholm Regionskommune in the basis analysis part 1. In addition, the Bornholm catchment management plan (Hovedvandopland 3.1) has been described by the Ministry of Environment. The overall assessment of the chemical and quantitative status of the regional and deep groundwater is good (see Section 6.9).

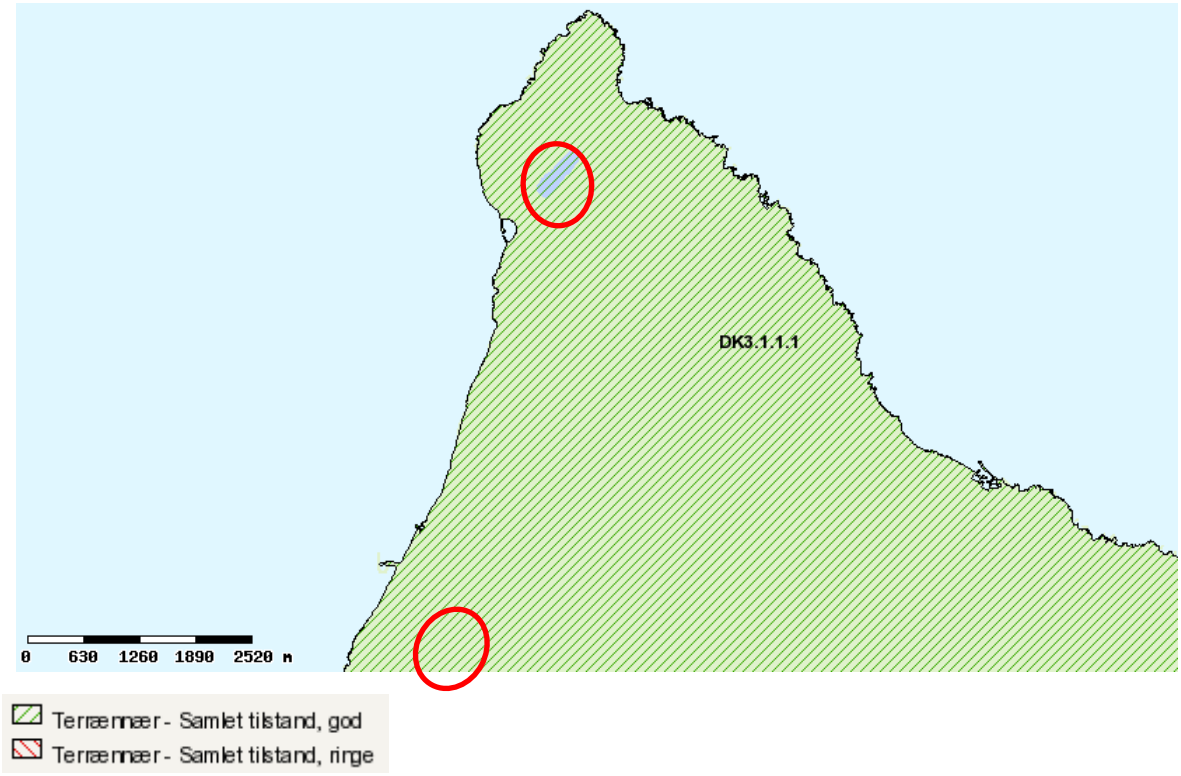


Figure 53. Shallow (or terrain near) groundwater body DK3.1.1.1. Red circle show the location of the two suggested locations of Area 2 in the Granite quarries in Hammeren or Vang. (From Miljøministeriet, 2010.)

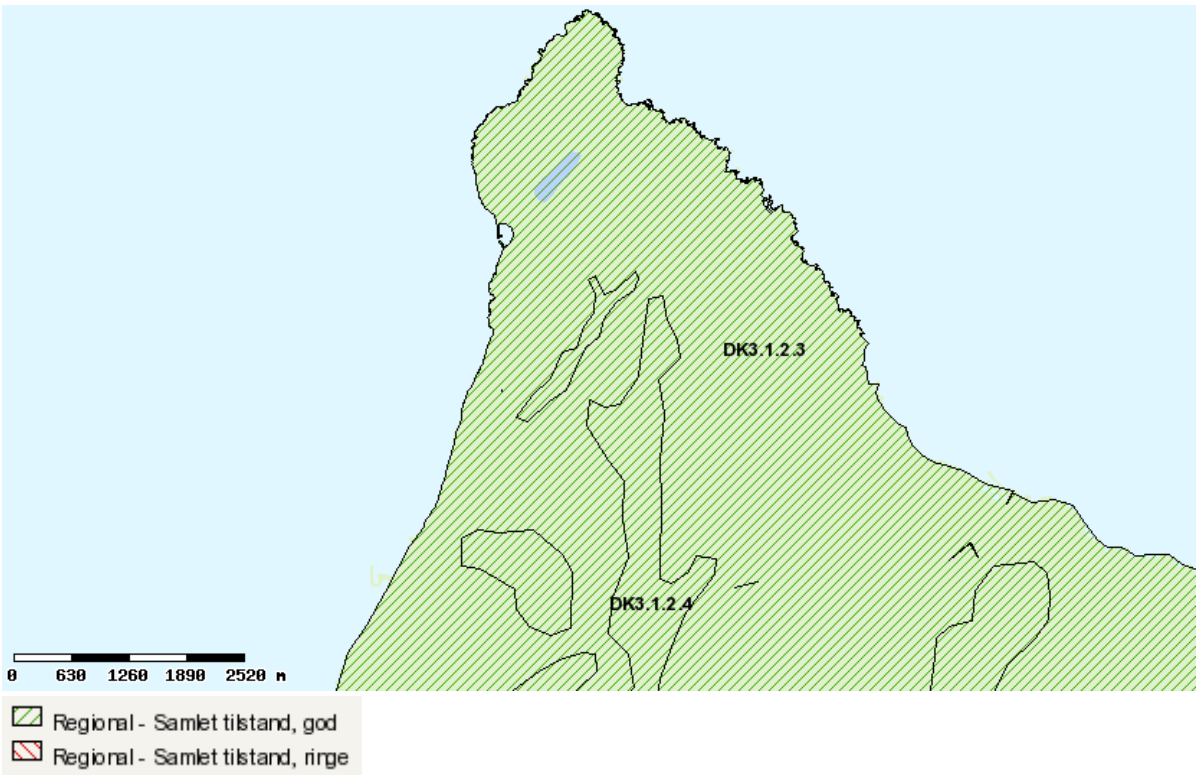


Figure 54. Regional groundwater body DK3.1.2.3 on northwest Bornholm (From Miljøministeriet, 2010).

Investigation of groundwater conditions, water supply and quality has been carried out in two areas on northern Bornholm covering the OSD and OD areas (see below, Fig. 55). The Hammeren and Vang quarry areas are outside these areas. At the Hammeren area, no groundwater data exists but at the Vang area, the nearby Kjøllergård abstraction area is located in the Ringdalen fracture valley.

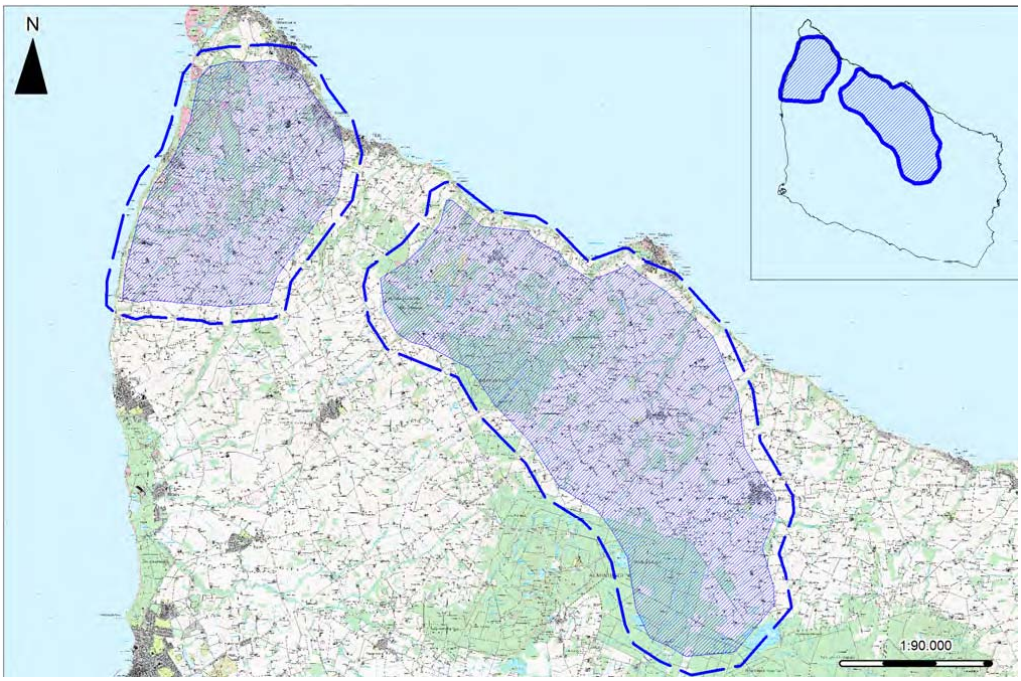


Figure 55. Groundwater and water work investigation areas on northern Bornholm. (From Roskilde Miljøcenter, 2009).

The information of the groundwater conditions in the two quarry areas is very sparse. Inspections in the quarries have demonstrated that surface water is transported in the fractures but the groundwater table is situated in a lower level. In the Hammeren Quarry, the lower part is water filled (Opalsøen) and level is higher than the level in the Hammer Sø. This indicates that it is surface water.

6.8.2 Drinking water areas

If it shall still be possible to pump clean drinking water, the groundwater has to be protected. It is the Environmental Centres (former counties) responsibility to do the planning, based on the two criteria: First, to make sure that the necessary quantity of clean groundwater can be abstracted in the future. Secondly, that the groundwater aquifers will be protected against recent and future pollution.

As part of government´s efforts to protect groundwater, the Environmental Centres have designated areas where major groundwater aquifers exist. The areas are named

OSD-areas: "Areas of special drinking water interests" (Fig.56). The rest of the country is divided into "Areas with water interests." Here are also good sources of drinking water. Finally, "Areas with limited drinking water interests." Here it is difficult or impossible to obtain good ground quality. The water is more or less contaminated.

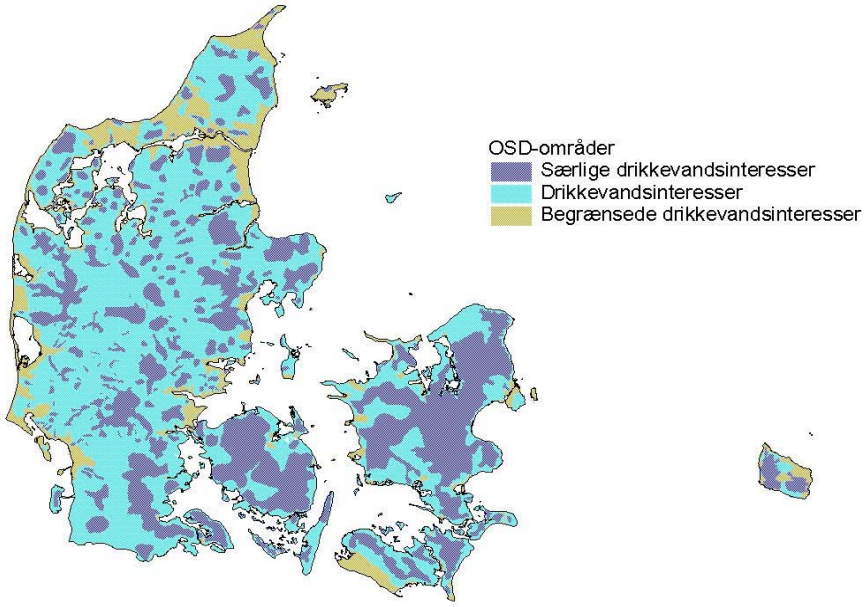


Figure 56. Map of three categories of drinking water interests in Denmark. The areas of special recharge groundwater and drinking water interests (OSD areas, protected by law) are in dark blue colour. The areas shown with light blue colour are areas of some interest for drinking water purposes. The areas in olive brown colour are areas of limited (or none) drinking water interests.

The drinking water areas (OSD and OD) can be seen on Fig. 57. The geographical distribution of the drinking water areas at northwest Bornholm is given in Fig. 57. As shown, both the suggested Area 2 locations are placed outside areas with the OD or OSD status. Fig. 58 illustrates the recharge areas together with drinking water interests.

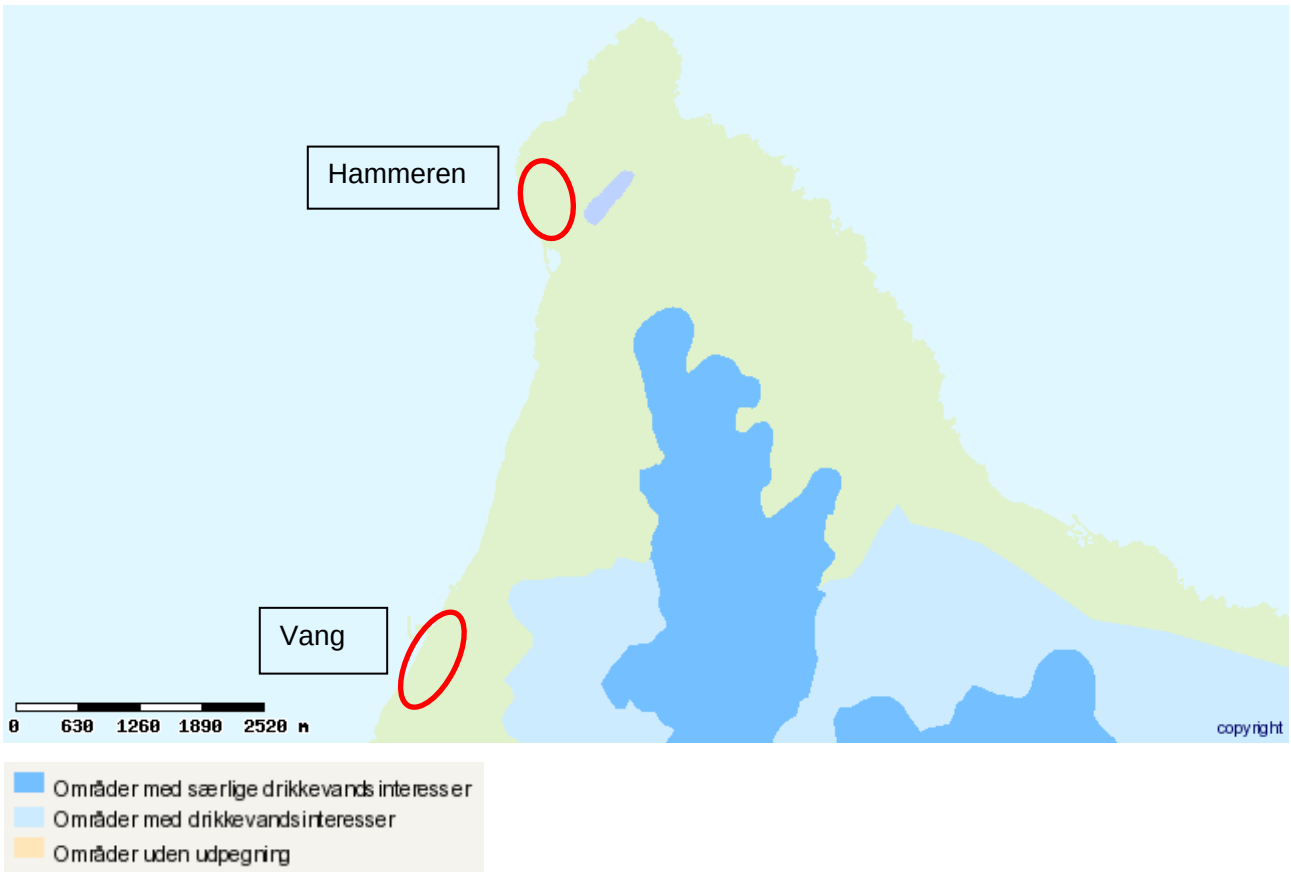


Figure 57. Distribution of the drinking water areas at northwest Bornholm and location of the two suggested locations of Area 2. Dark Blue: Areas of special drinking water interests (OSD); Light blue: Areas of some drinking water interests (OD); Yellow green: Areas with limited or none drinking water interests (From Miljøministeriet, 2010).

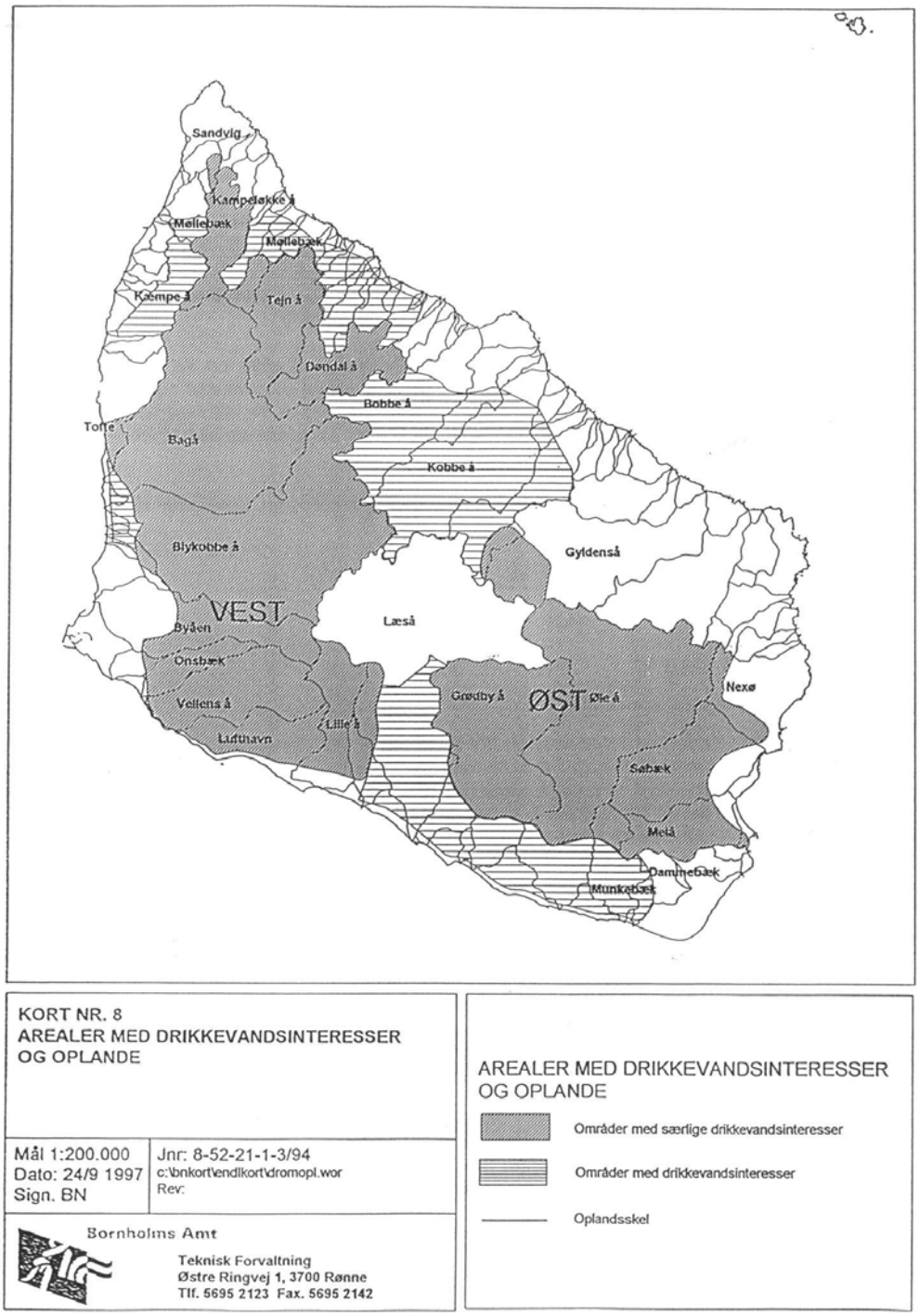


Figure 58. Recharge areas and drinking water areas. (From Bornholms Amt, 1997).

6.9 Groundwater Geochemistry

There is no information from the two areas. The overall groundwater quality aiming for drinking water purpose has been assessed by Bornholm Regionskommune and Environmental Centre Roskilde for the shallow and regional groundwater body and reported in the catchment management plan “Hovedvandopland 3.1, Bornholm“. The groundwater chemistry fulfils the EU criterions to be of good status.

Vang: Abstraction wells belonging to Vang water work indicate chloride contents between 25 and 50 mg/L. This means that sea water intrusion is not expected to be a problem at the Vang location.
Hammeren: No wells are registered in JUPITER at Hammeren. Thus, the chloride content in groundwater at Hammeren is uncertain.

6.10 Climate and climate changes

The actual climate and the expected future climate changes and sea level development is described in Gravesen et al. (2010, Rep. No. 2). It is obvious, that more and more intense rain may raise the discharge of the very few streams, that are located in Area 2a and 2b and raise the water level of the lakes in the quarries. A sea level rise does not cause any troubles for Area 2a and 2b. It is unclear if and how more and more intense rain will influence on groundwater level.

6.11 Restrictions and limitations

The suggested location of Area 2 at Hammeren is positioned in a Natura2000 habitat area (Fig. 59).

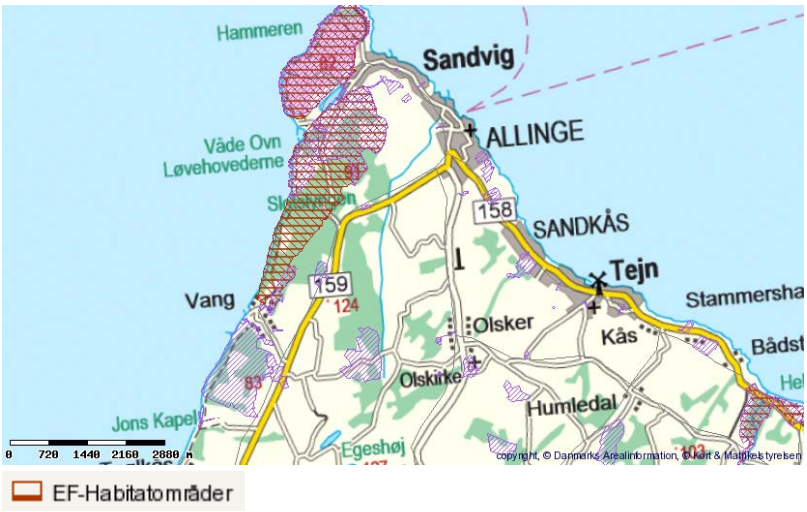


Figure 59 NATURA2000 habitat areas (Red horizontal lines) and protected areas (Hatched purple lines) of northwest Bornholm. (From Miljøministeriet 2010).

The Hammeren and Vang locations both lie outside the OSD and OD areas. However, few miles east of Vang lay an OSD area. The Hammeren area has no groundwater abstraction, while Kjøllergård water supply in the fracture valley (sprækkedal) is very closely located to the Vang area. The major fracture systems observed in both the Vang and Hammeren Quarries need further investigation in order to clarify their possible impact on groundwater flow and contaminant transport. The suggested Hammeren location is only possible as a deep repository facility due to special considerations of Nature 2000 conditions in the Hammeren area.

The two areas are covered by a series of other restrictions. Hammeren is a protected area. Several ancient monuments occur in the area. Areas of National Geological Interests comprise Hammeren and the coastal areas to Allinge on the north-eastern side of Bornholm and to Krammedal on the west part.
Quarrying of Hammer Granite has been stopped for many years. The quarrying of Vang Granite in Vang and Almeløkke Quarries has now recently been stopped and the permission has not been renewed. The areas around the quarries are now protected.

6.12 Summary of the area conditions

Amount of data:
Very Sparse: Boreholes and geophysical surveys. Abundant fracture and fault data can be collected in the field.

Homogeneous conditions and isolation of the waste by low, permeability layers:
Perhaps perfect on depth below 50 – 80 m but the framework of the fractures below 20 m is unknown. The fracture problem has to be considered as this is a major problem.

Stability
Good stability on surface and depth is expected.

Seismic activity and tectonic movements
No seismic and tectonic movements give problems.

Groundwater conditions
The special groundwater conditions in bedrocks should be positive but the variation in the groundwater table has to be analysed if the disposal has to be establish under saturated conditions. The distance to the sea is very short.

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

Drinking water interests

No OSD or OD areas are conflicting with the Area 2. Only minor local supplies occur.

Groundwater chemistry, non-aggressive components

The groundwater contains apparently no aggressive components.

Ground surface conditions

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

Climate extreme conditions

Climate changes and extremes will not have influence on a disposal.

Other restrictions

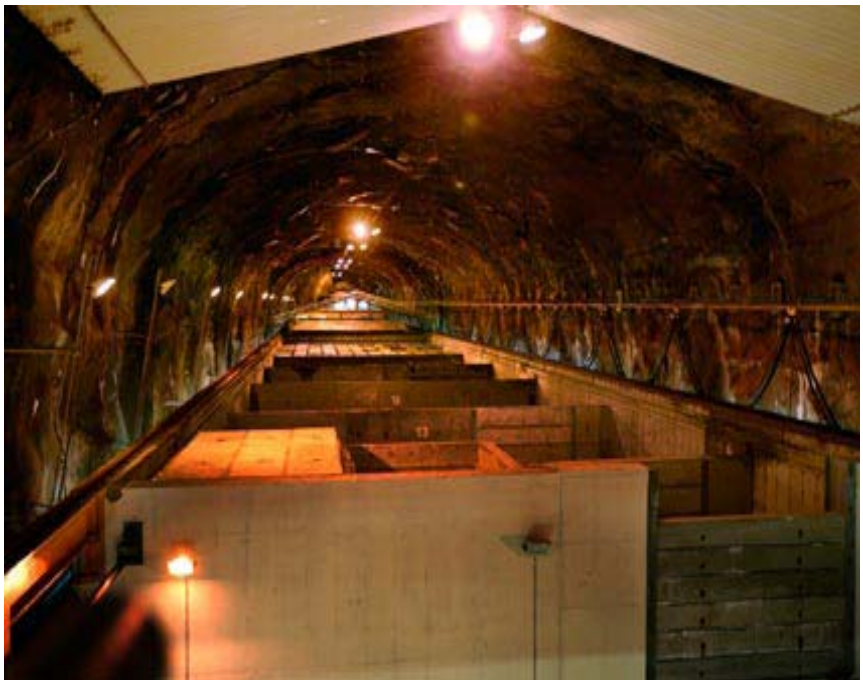
Area 2a is located inside one of the Danish sites of national geological interest (no. 183a). Area 2b includes one of the Danish sites of national geological interest (no. 184).

No other restrictions will give problems, but the relationship to NATURA2000 and Protected areas have to be considered.

6.13 Final remarks

In Sweden and Finland, low and intermediate level waste disposals are located in Precambrian basement rocks. At Forsmark (Sweden), the waste is placed in tunnels and caverns in the rocks 50 m below the sea bed surface within other shielding (see photo below). The storage chambers consist of four 160 m long caverns and a 70 m high cavern with a silo. The Finnish caverns are situated 100 m below ground surface. The Swedish basement rocks also suffer of fractures to large depth but the conditions in the area have pointed this disposal solution.

The two areas on Bornholm give different possibilities: A construction from the ground surface or from the bottom of granite quarries. The two subareas are different in relation to fracture intensity and weathering and therefore, they should be considered separately.



The low and intermediate level radioactive waste disposal at Forsmark (Sweden) stored in Precambrian basement rocks.

7. Reports in the Waste Disposal Series:

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Published in GEUS Report Series.

Report No. 1. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2010: Data, maps, models and methods used for selection of potential areas. GEUS Report no. 2010/122, 47 pages.

Report No. 2. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2010: Characterization of low permeable and fractured sediments and rocks in Denmark. GEUS Report no. 2010/123, 78 pages.

Report No. 3. Pedersen, S.A.S. & Gravesen, P.., 2010: Geological setting and tectonic framework in Denmark. GEUS Report no. 2010/124, 51 pages.

Report No. 4. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Bornholm. GEUS Report no. 2011/44.

Report No. 5. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Falster and Lolland. GEUS Report no, 2011/45.

Report No. 6. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Sjælland. GEUS Report no. 2011/46.

Report No. 7. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Langeland, Tåsinge and Fyn. GEUS Report no. 2011/47.

Report No. 8. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of Areas. Eastern Jylland. GEUS Report no. 2011/48.

Report No. 9. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Limfjorden. GEUS Report 2011/49.

Report No. 10. Gravesen, P., Nilsson, B., Pedersen, S.A.S. & Binderup, M., 2011: Characterization and description of areas. Nordjylland. GEUS Report 2011/50.

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