DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2010/124

Low- and intermediate level radioactive waste from Risø, Denmark. Location studies for potential disposal areas. Report no. 3

Geological setting and tectonic framework in Denmark

Stig A. Schack Pedersen
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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 potentials.
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, hydrogeological – hydrochemical and technical conditions will be performed.

In Denmark, various kinds of fine-grained sediments and crystalline rocks occur from the ground surface down to 300 meters depth. Therefore, the possible geological settings include sediments and rocks of different composition and age. These settings are geographically 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 geological and structural framework of Denmark as background for the comprehensive evaluation of areas.

1.1 The aim of this report

This report provides an introduction to the geological setting of Denmark with the focus on providing an overview of the distribution of various tectonic and structural features. These are considered important in the context of choosing suitable areas for the location of a disposal for radioactive waste. The report gives the information and supplement to the description of low-permeable and fractured sediments and rocks in Gravesen et al, (2010, Report no. 2). The geological structures, deep and shallow are important for the selection of potential disposals basically because the structures describes the geometry of the areas. Additionally, the structures provides the information about the risk of unwanted movements of the geological layers around the disposal that have to be investigated and evaluated as a part of the selection process.

2. GEOLOGICAL SETTING OF DENMARK

Denmark is lowland with hills generally less than 150 m high (Fig. 1). The main part of the land is characterized by a glacio-morphological topography with fjords incising the former tunnel valleys. The Main Stationary Line forms a characteristic boundary down through Jylland, west of which huge sandur plains and erosion remnants of the Saalian landscape are situated. The most significant addition to the land after the ice age is the Skagen Odde, which forms one of the biggest spit systems in the world. The spit system (odde) started to form during the forced regression at the transition from the Pleistocene to the Holocene about 12.000 years ago (Nielsen & Johannessen, 2009) and is closely related to the main

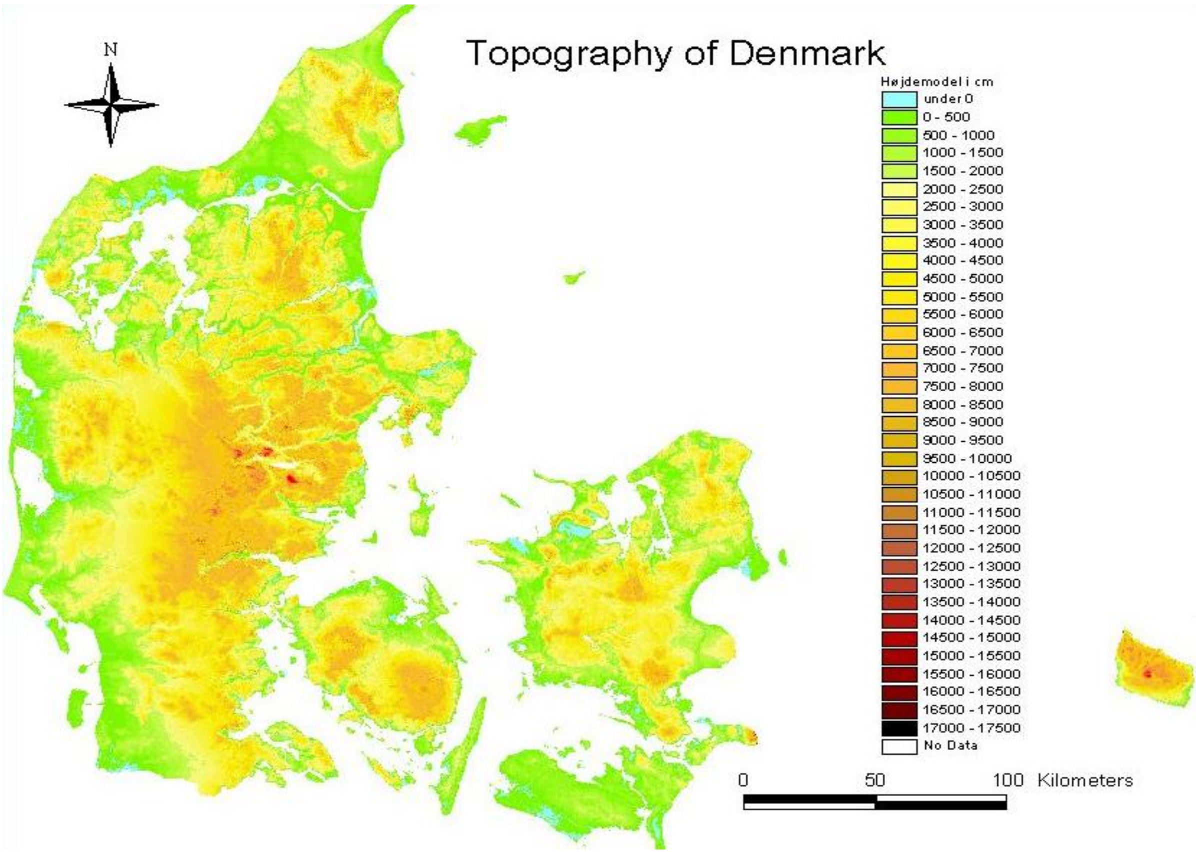

Figure 1. Topographic map of Denmark. Note that the highest elevated areas are located in the central part Sjælland, the central part of Fyn, the central part of Bornholm and the central eastern part in Jylland. Moreover, high-elevated areas occur in Skovbjerg Bakkeø in the central part of western Jylland and in Jyske Ås in the north and eastern part of Vendsyssel.

uplift of Vendsyssel, the landscape south of the spit, which was isostatically uplifted 20–50 m above sea level during the last 15.000 years (Mertz, 1924). South of Vendsyssel, the Limfjorden forms a strongly incised and branching fjord and inner sea system, which only 8.000 years ago was open to the west, where it formed an archipelago on the transition to the North Sea.

During the isostatic uplift and the formation of beach ridges along the west-coast of Jylland, the western part of Limfjorden had no connection to the North Sea for about 1000 years and ended up as a fresh water sea. A winter storm in 1823 re-established the western entrance to the Limfjorden, which since that time have remained a salt-water fjord system.

In the southern part of Denmark, the land is subsiding and drowned by the Atlantic transgression. This resulted in the archipelago Smålandsfarvandet, where the islands constitute a drumlin dominated moraine plateau (Pedersen & Rasmussen, 2000) and the archipelago south of Fyn. The archipelagos are separated from northern Europe by the western part of the Baltic Sea. To the east, the Øresund strait and the Kattegat Sea separate Denmark from Sweden. To the north, the deeply eroded Skagerrak Sea disconnects Norway from Denmark, and to the west, Denmark is bordered by the North Sea. Along the southern part of this coastline, the Wadden Sea area is located, from where the border between Denmark and northern Germany crosses the peninsula Jylland from the North Sea to the Baltic.

2.1 The pre-Quaternary Geology of Denmark

The geological map of the Danish bedrock is shown in Fig. 2. The geological setting of northern Denmark is related to the main tectonics of the Norwegian–Danish Basin (Danish Sub-basin). A very strong element in this setting is the Sorgenfrei–Tornquist Zone, which is a NW-striking fault zone separating the Scandinavian Basement to the north and east from the up to 10 km deep basin to the south and west. The main fault activity in the Sorgenfrei–Tornquist Zone took place about 60 million years ago, but earthquakes in southern Scandinavia are still concentrated along this zone. Towards the south, the Ringkøbing–Fyn High forms a basement area, which separates the Danish Sub-basin from the North German Basin (Fig. 5).
In the Danish Basin, the oldest sediments are from the Early Cambrian, but generally, the Lower Palaeozoic is not very well known in the subsurface of Denmark. The lower Palaeozoic sedimentary rocks crop out on the southern part of the Baltic island Bornholm, and the northern part of the island comprises basements rocks 1500–1300 millions years old.
The Upper Paleozoic time is characterized by Permian salt, whereas sedimentary rocks from the Devonian and Carboniferous are nearly absent in the Danish Basin. The Zechstein salt is overlain by a more than 3 km thick succession of Triassic siliclastic sediments. The deposits comprise mainly red sandstones deposited on huge fluvial plains characterised by aeolian dune formations. The considerable thickness and relative fast deposition of the Triassic deposits contributed to the formation of salt diapirs. The overlying Jurasssic deposits mirrors the marine transgression in Northern Europe during the onset and climax of rifting in North Atlantic region (Surlyk & Ineson, 2003). The Lower Jurassic consists of thick marine clays but more sandy deposits occur up-

wards (Nielsen, 2003). The deposits are exposed in fault blocks along the west and south-west coast of Bornholm, where the clayey mudstone, sandstone and interlayered coal beds represent tidal and paralic environments. The Jurassic deposits crop out on the pre-Quaternary surface in the Rønne Graben and along the inversion swell in the Sorgenfrei-Tornquist Zone in the Kattegat Sea, from where they can be traced along strike into the exposed outcrops in southwestern Sweeden (Vejbæk & Andersen, 2002, Gravesen 1996). Furthermore the Jurassic deposits are present in the subsurface of the Norwegian-Danish Basin with thickness exceeding one km in the depressions related to the Fjerritslev Fault Zone (trending SE–NW across northern Denmark) and in the Central Graben in the North Sea (Vejbæk, 1997).

The Cretaceous chalk forms the northern part of the large North European carbonate platform. The upper Cretaceous Maastrichtian chalk crops out on the pre-Quaternary surface in the Kattegat Platform and in the Baltic area. The chalk is exposed in the Portland pits in northern Denmark, in the centres of some of the salt-diapir produced domes, and in the glaciotectonic complex at Møns Klint in southeastern Denmark (Pedersen, 1992).

In the upper part of the so-called “Chalk Group”, the stratigraphic boundary between the Mesozoic and Cenozoic rocks is included. The famous Cretaceous/Tertiary boundary forms the lower boundary of the Danian Limestone, which is dominantly present in the subsurface of Denmark (Surlyk 1980). The Danian Limestone constitutes bryozoan reef limestone interbedded with chert. In few localities, choral limestone is present, and the limestone succession grades up into a hard, massive limestone named the København Formation. The best-known locality for the Danian Limestone is Stevns Klint (central eastern Denmark), where the Fish Clay with the high iridium-content contributing to the interpretation of the “big bang” hypothesis is exposed (Surlyk et al. 2006).

In Denmark, the Paleogene constitutes clay-rich formations, which represent a temperate sea environment. In the northern part of Denmark a remarkable succession of clayey diatomite interlayered by volcanic ash beds occur, the Fur Formation (Pedersen & Surlyk 1983). The ash layers mirror the volcanic activity related to the early break-up of the Laurentien continent and the formation of the North Atlantic Ocean on the Paleocene/Eocene boundary (Larsen et al, 2003). The diatomite formation with volcanic ash layers can be traced into the North Sea, where they are recognised as the Sele and Balder Formations (Rasmussen et al., 2005).

The ocean spreading tectonic event started about 55 million years ago and was associated with an impressive volcanic activity. Volcanic rocks were deposited in Scotland and East Greenland. In the middle of the ocean, the Færø Islands were formed, which subsequently with the opening of the ocean drifted to the east together with the Norwegian shelf giving space for Iceland to be created in the last 4 million years of the geological history (Larsen et al., 2003).

Marine Oligocene clay and silt beds are known from the eastern and middle part of Denmark and the clays consist of fine-grained and silty, often micaceous, types. The Neogene is dominated by a large delta system building out from the North-East European–Baltic platform towards the North Sea in the Miocene time (Rasmussen, Dybkjær & Piasecki, 2002). These deposits dominate the western part of central Denmark, and they continue into the Norwegian-Danish Basin in the North Sea, where a kilometre-thick accumulation of sandy units fills the depocentre above the Central Graben. Apart from the delta system, parts of the Miocene in mid-Jylland consist of thick sandy successions containing lignite deposits. Towards the west, marine Miocene deposits containing clays, silts and fine-grained sands reach large thicknesses.

3. GEOLOGICAL – TECTONIC FRAMEWORK

3.1 The geotectonic margins of the Danish Basin

The tectonics in the Danish Basin is strongly dominated by the Sorgenfrei-Tornquist Zone. This zone extends from the Baltic Sea, where it includes the island of Bornholm and the Rønne Graben, crosses the south-western corner of Sweden, from where it trends up through the Kattegat in the direction of Anholt. From this central part of Kattegat, it extends further up towards the eastern part of Limfjorden (Liboriussen et al., 1987). One of the prominent faults in the Sorgenfrei-Tornquist Zone is the Fjerritslev Fault, which strikes to the NW from Fjerritslev and continues into the Jammerbugt and up to the North Sea, where it links up with the fault complex in the Egernsund Basin off the south coast of Norway (Fig. 2). Northeast of the Sorgenfrei-Tornquist Zone, Precambrian basement crops out in Sweden and Norway. The boundary to the basement is generally referred to as the Fenno-Scandian Border Zone. The Børglum Fault, crossing Vendsyssel SE–NW, comprises the northern limit of the Sorgenfrei-Tornquist Zone. Between this fault and the Fenno-Scandian Border Zone, a platform area mainly occupied by Upper Cretaceous chalk, Lower Cretaceous and Jurassic sandstones is referred to as the Kattegat–Skagerrak Platform (Fig. 3). This platform area extends up to the southern part of the Oslo Graben (Fig. 2), which is characterised by syenitic plutonic intrusions and lava successions, the rhomb porphyries, a well know source province for erratics, distributed throughout the western part of the Danish Quaternary.
The western part of Denmark is bordered by the North Sea Basin with the Central Graben forming the westernmost boundary complex of the Danish offshore territory. The main part of the North Sea Basin is covered by several hundred meters of Neogene deposits. The eastern limit of these deposits can be traced from the western Limfjorden area towards eastern Jylland, where the boundary between Neogene and Palaeogene deposits follows a zone paralleling the coast of eastern Jylland.
Denmark is bordered by the North German Basin to the south. The basement under the south coast of Falster, Lolland, Langeland and Als is gently dipping towards the south. The successions of Palaeozoic and Mesozoic sediments increase in thickness until they are met with the front of the concealed Cadomian (Caledonian) fold belt. In southern Jylland, the Tønder Graben forms a narrow tectonic depression extending from Flensborg Fjord to Rømø.

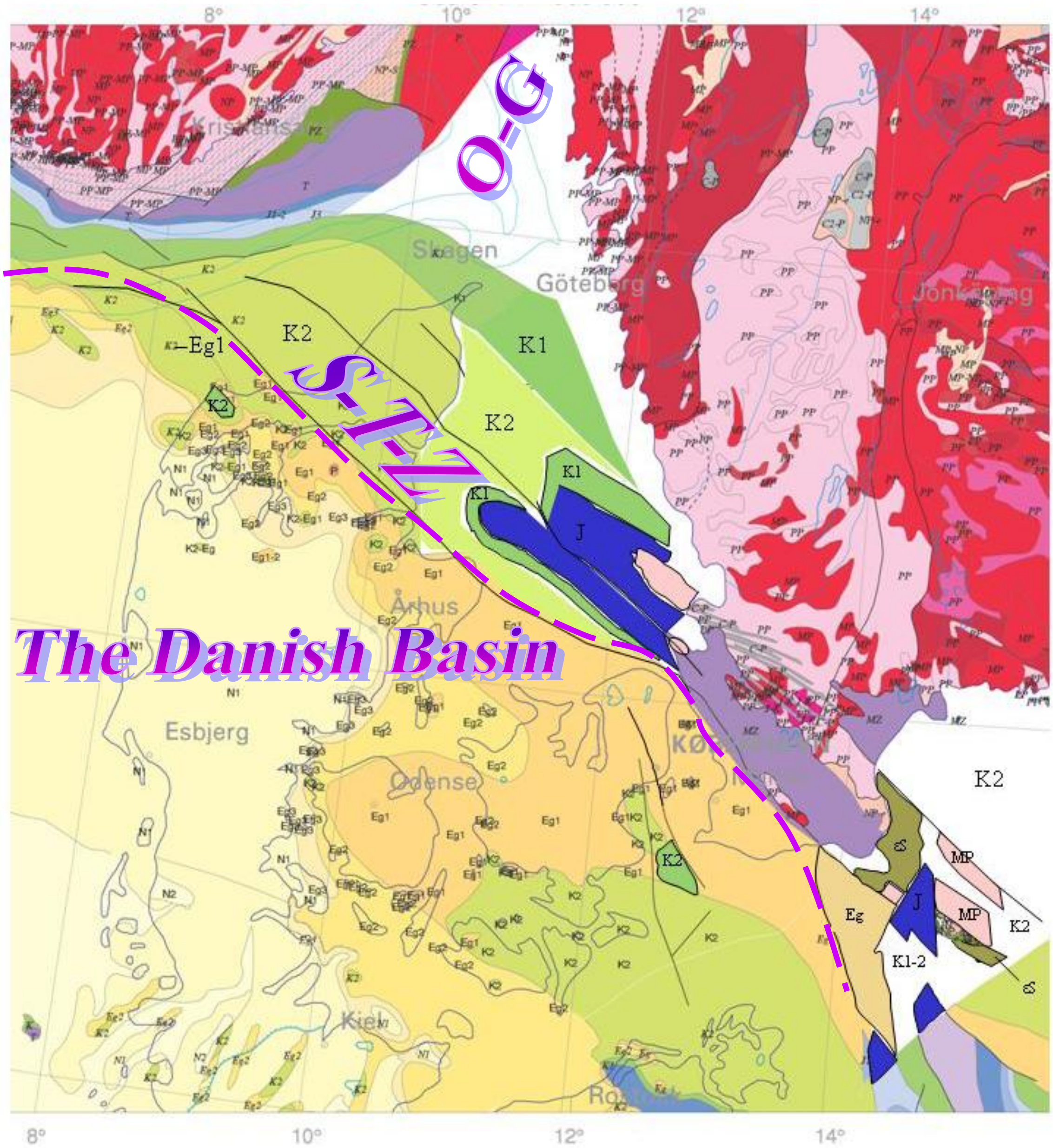

Figure 2. Pre-Quaternary map of Denmark. Red colours are Precambrian basement rocks at the margin of the Danish Basin. Blue colours are Jurassic and Triassic units, mainly occurring in fault blocks in the NW-SE striking Sorgenfrei-Tornquist Fault Zone (STZ). Green colours are Cretaceous chalk (K2), yellow-brown colour (EG1) is lower Tertiary limestone and marly clay. The light beige colour (N1) is Miocene sand deposits, which 15 million years ago formed a huge delta setting for the rivers draining the mainland of Europe out towards the North Sea. Between EG1 and N1, a number of clayey units appear mirroring the marine conditions under fluctuating water levels. O-G is the Oslo Graben, which is characterized by Permian volcanics. (Modified from Pedersen et al., 2002 and Pedersen, 2009).

3.2 Deep-seated tectonic structures

In the subsurface, the Precambrian basement forms a distinct WNW-ESE trending swell, the Ringkøbing–Fyn High, which separates Denmark into the Norwegian-Danish Basin towards north and the North German Basin towards south (Fig. 3). The basement swell, known from the deep wells in Denmark with the shallowest depth of 800 m on Fyn (in the Glamsbjerg well) and 1500 m in the well at Grindsted in the central part of Jylland, is separated by a few N-S trending grabens, Horns Graben to the west and the Brande Trough in central part of Jylland. The Ringkøbing–Fyn High fades out in the subsurface of the Baltic between Møn and Bornholm.

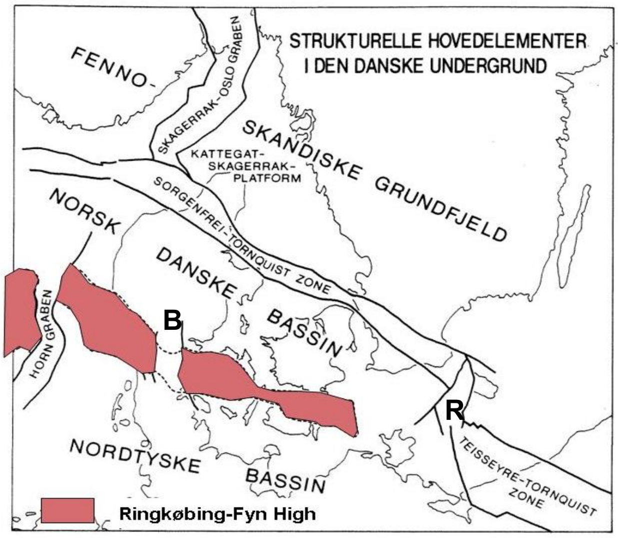

Figure 3. The basin division of the Danish subsurface, which is governed by the position of the Ringkøbing–Fyn High. B is the location of the Brande Through, and R indicates the Rønne Graben, which forms the western boundary of the basement horst comprising the main part of the island Bornholm. (From Håkansson & Pedersen,1992)

Bornholm is the only place in Denmark where outcropping Precambrian basement is found. The island constitutes a horst, with basement rocks occupying the northern half of the island. These rocks are best correlated to the basement rocks in southern Sweden.

The basement rocks are located at relatively shallow depth under the Kattegat-Skagerrak Platform (Fig. 3), where the north-eastern boundary fault of the Sorgenfrei-Tornquist Zone is represented by the Børglum Fault, along which the Precambrian rocks are normally displaced in the order of a kilometre (Vejbæk, 1997).

4. SALT DIAPIRS

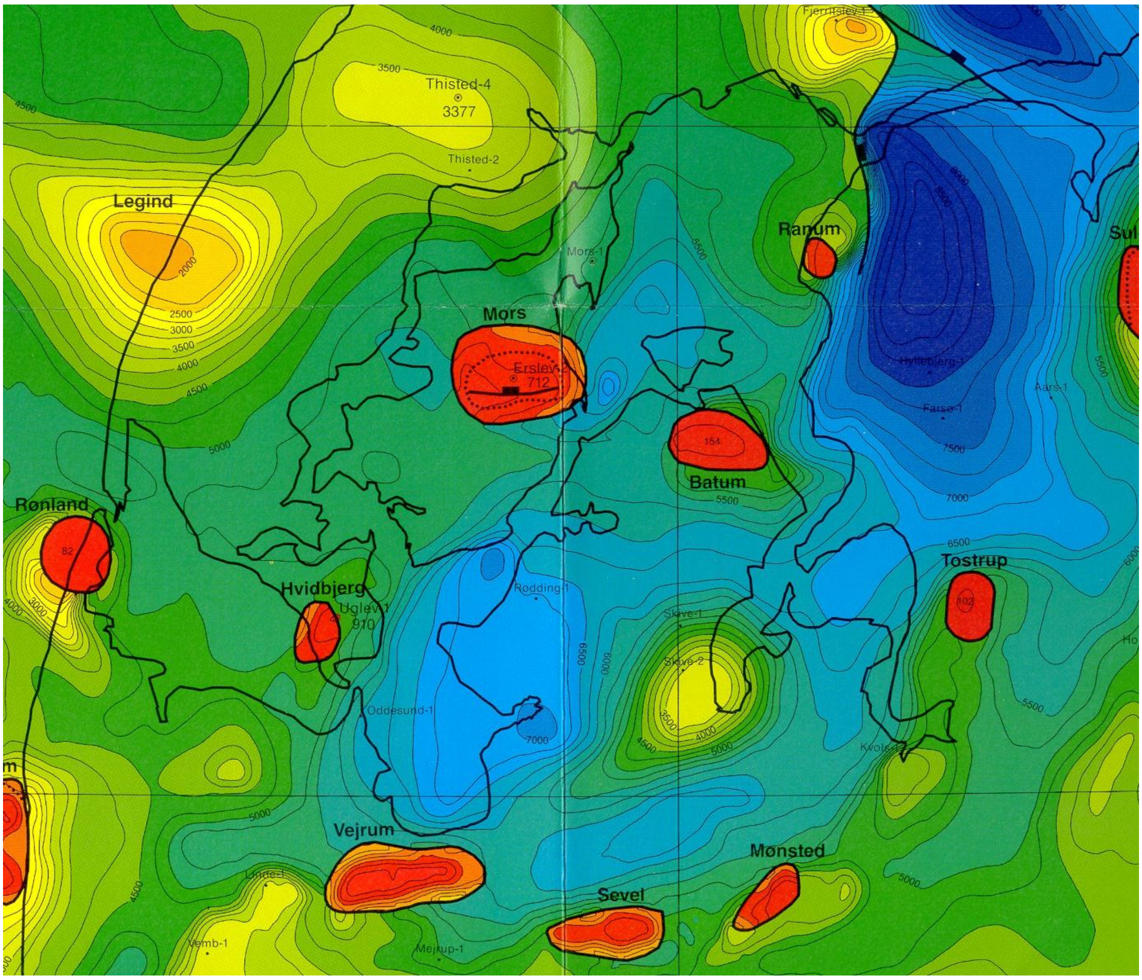

Figure 4. Location of the salt diapirs (red areas) in the salt diapir province of the western Limfjorden region. The contours show the depth to the Zechstein salt, which was deposited in the Late Permian period. Thus, it can be seen that in the Batum diapir, the salt is only 154 m below ground level, whereas the main salt layer, from where the salt diapir rises, is situated in 5–6 km depth. (From Britze & Japsen, 1991).

Some of the marked structural elements in the Danish subsurface are the salt diapirs. The salt was deposited in the depressions north and south of the Ringkøbing–Fyn High in the Late Permian period about 250 million years ago. In general, it is referred to as the Zeichstein salt, and the main diapirism was initiated during the Triassic. The depth to the Permian salt varies a lot. In northern Denmark, the depth to the Permian salt is more than 6000 m. From this depth, the salt has migrated up in diapirs with a top located only a few hundred meters below present surface (Fig. 4).

The elevated salt structures comprise salt diapirs as well as salt pillows, and they occur dominantly in two provinceds: the western Limfjorden region (Fig. 4) and the North German Salt Province (Fig. 5). Moreover, scattered occurrences of individual salt pillows are present in the central part of Denmark north of the Ringhøbing-Fyn High and southeast of the Sorgenfrei-Tornquist Zone.

4.1 The salt provinces in Denmark

The salt structures in the western Limfjorden region are concentrated in a ring-like distribution around a faintly elevated dome located below the town Skive (Fig. 4). In the southern side of the ring, the diapirs Vejrum, Sevel and Mønsted are located. The ring can be traced from Mønsted to the Tostrup structure on the east side, and on the north side, the Batum and Erslev structures form very marked diapirs, which strongly influenced the upper Mesozoic and lower Cenozoic deposits. Between the Erslev structure and the Vejrum structure, the Hvidbjerg diapir represents the western side of the ring. However, further to the west, a series of additional diapirs occur, which are lined up on a trend towards the North Sea to the NNW. Two large salt domes are situated between the “Limfjorden ring” and the North Sea diapirs, namely the Legind and the Thisted structures.

The general indication of the present of salt structures in the Limfjorden region is the present of Upper Cretaceous Chalk or Danian limestone outcropping below a thin cover of Quaternary deposits or even exposed at the surface. A typical example of the monoclinal bend of the bedrocks up along the side of a salt diapir is illustrated in Fig. 6, which show the seismic cross section of a salt structure in the “salt ring complex”. This structure is located on Thyholm, where the deposition of chemicals in abundant open chalk pits has caused serious problems to the local authorities. The expression of the salt structure mapped by means of contour lines, based on the wells on top of a salt structure, is shown in Fig. 7. This structure is part of the Batum structure on the east side of the “salt ring complex”, which was one of the earliest investigated salt structures in Denmark. The re-cognition of salt structures was originally based on gravity mapping of Denmark in the early part of 1950–60.

On the north side of the Ringkøbing–Fyn High, salt structures are known from Hobro, the Hvornum structure, which is excavated by ex-solution caverning for the Danish salt production. Southeast of Hobro, the Gassum and Voldum structures should be mentioned. The shield formed cover above these structures has formerly been the target for gas-exploration and the structures might be the target for geothermal reservoirs in the future (Michelsen et al. 1981). Along a line from Vemb to Horsens, a small number of structures occur, and in the northwestern part of Sjælland, similar smaller structures have been identified. The two salt pillows at Hvalsø and Stenstille are the most prominent structures from the salt regime at Sjælland (Fig.5).

South of the Ringkøbing–Fyn High, salt structures are known from Tønder and Rødby (Fig. 5). However, these are only the most significant among a number of smaller pillows and domings of the salt along the faults dipping towards the North German Basin (Fig. 8).

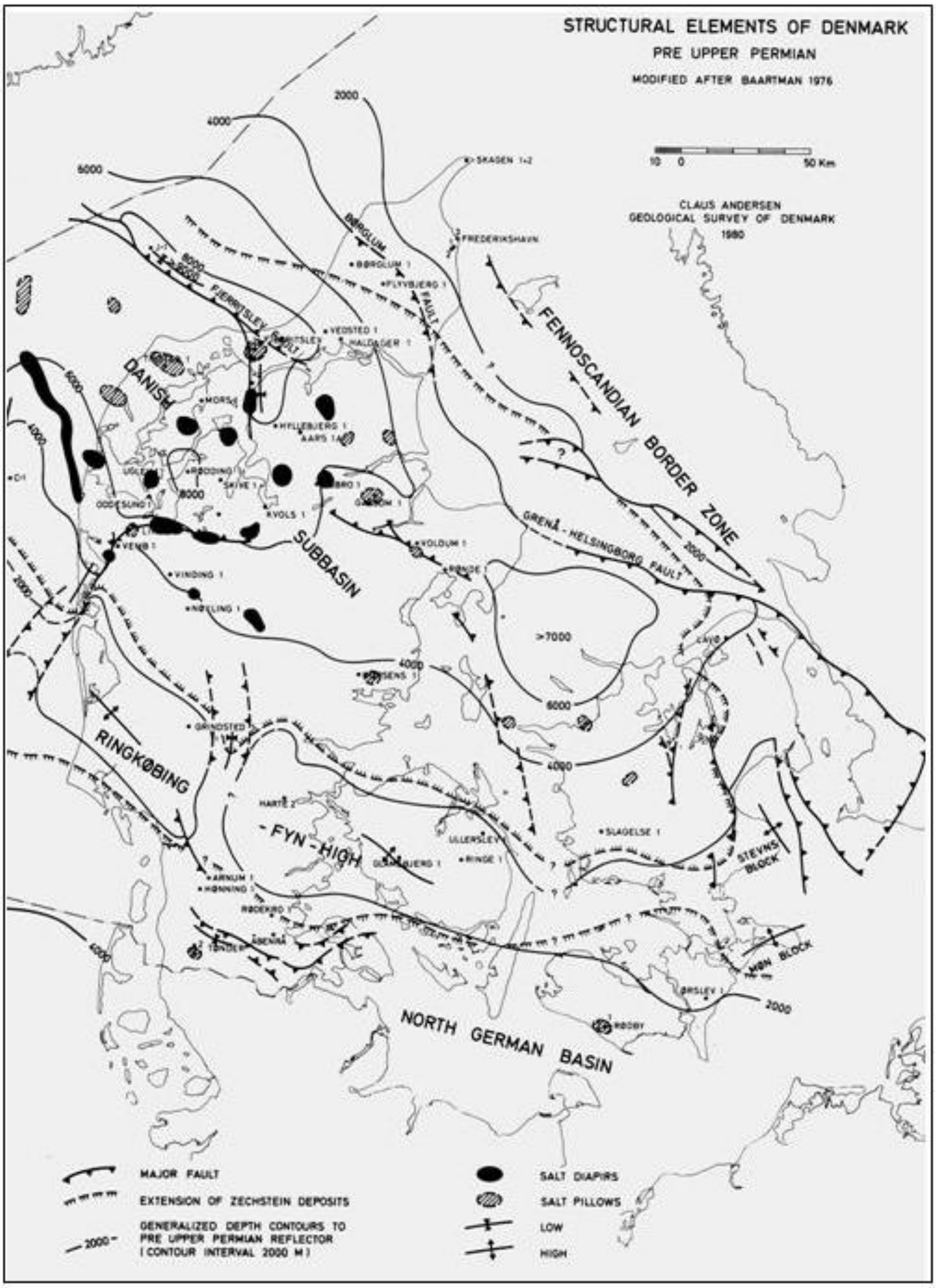

Figure 5. Map of the structural elements related to the Zechstein salt structures. (From Michelsen et al., 1981).

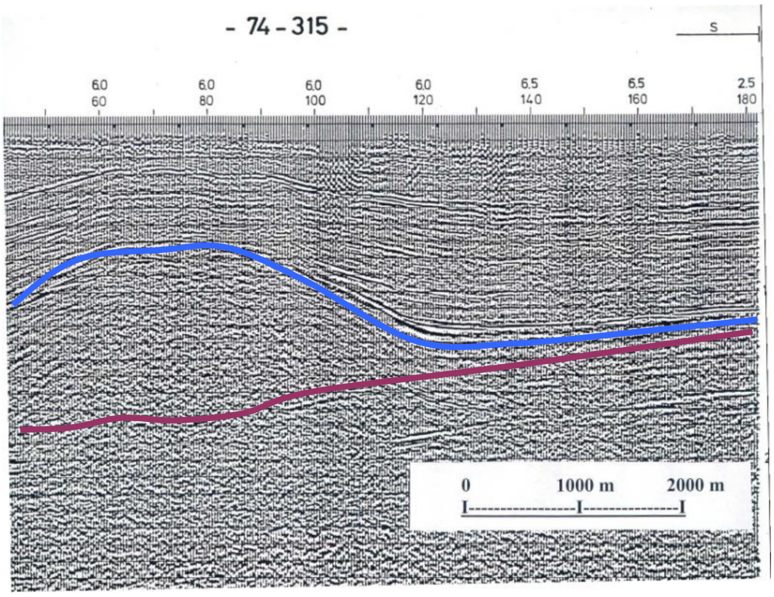

Fig. 6. Seismic section of a salt dome, here the Hvidbjerg salt structure on Thyholm, the western part of the western Limfjorden region. The blue line indicates the top of the salt, and the purple line outlines the base of the salt (Rotliegendes).

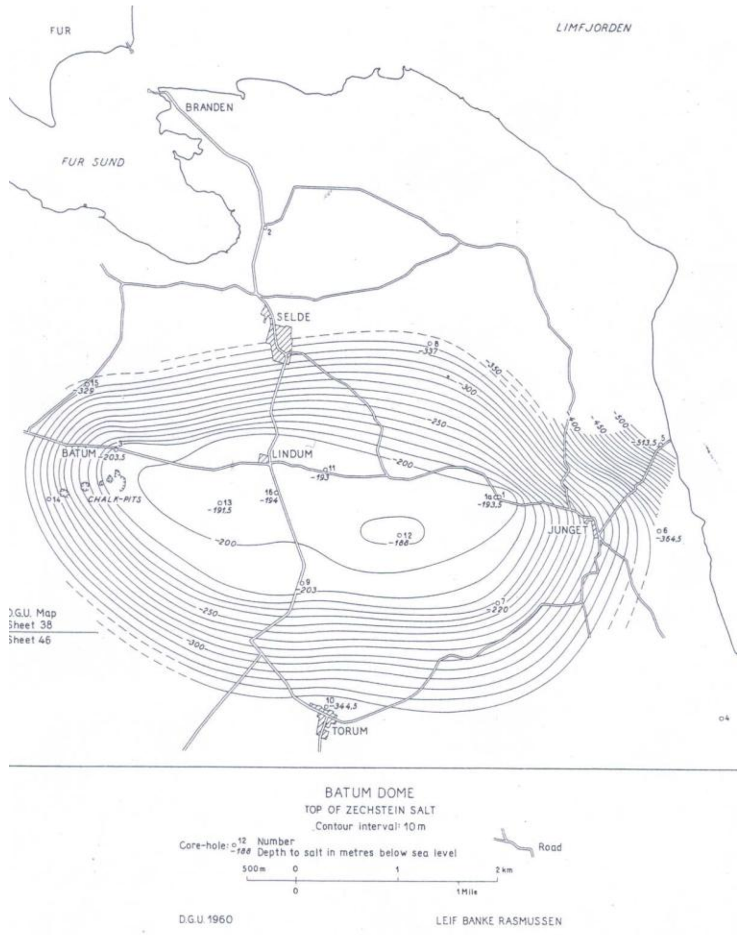

Figure 7. Contours outlining the top of the Batum Salt Dome. (From Rasmussen, 1960).

5. TECTONICS OF CRETACEOUS AND TERTIARY DEPOSITS

The tectonic activity in the Danish Basin was very intensive in the Late Cretaceous time extending into the early Paleocene. Particularly the eastern part of the basin was affected by subsidence in smaller elongated basins along the Sorgenfrei-Tornquist Zone, which was subjected to inversion along the formerly active faults in the Paleocene (Fig.5). This tectonic event was dominantly affecting the area around Anholt and the Rønne Graben west of Bornholm (Vejbæk, 1997).

Very few structures seem to cut the pre-Quaternary surface (se chapter 7) or the Quaternary sediments (se chapter 12). The lack of information, mainly geophysical survey data is probably the reason for this. New geophysical information together with well-dated borehole samples will improve our knowledge of this in the future.

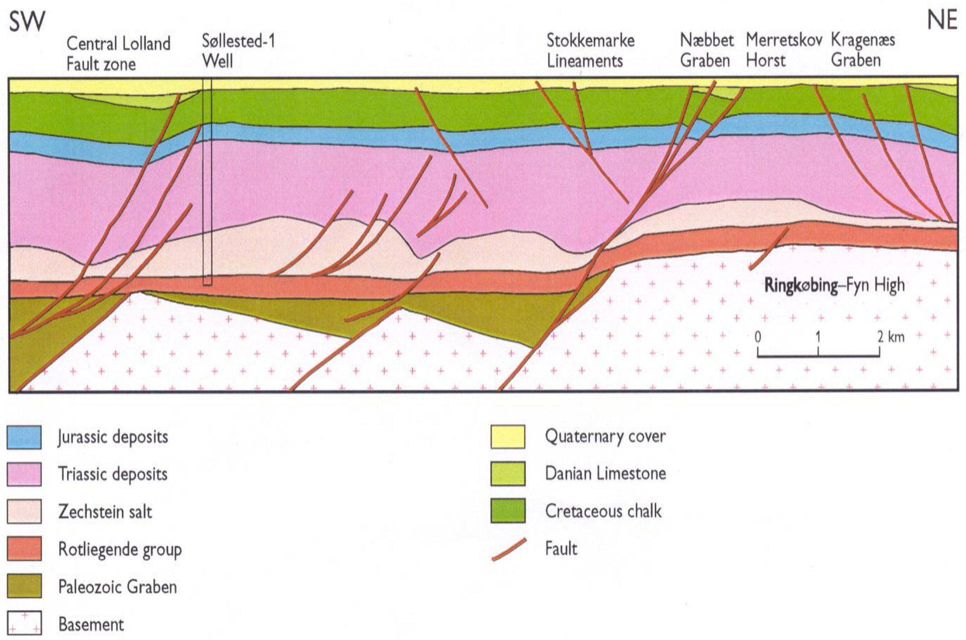

Figure 8. Geological section from the northern part of Lolland showing the fault patterns from the basement reaching up into the Danian sediments and perhaps also into the Quaternary sediments.

6. TECTONICS OF BORNHOLM: BASEMENT, BLOC TECTONICS AND INVERSION

Bornholm is the easternmost island of Denmark, situated in the Fenno–Scandian Border Zone (Sorgenfrei–Tornquist Zonen) with the Fenno–Scandian Shield towards the north and the Danish–Polish Trough towards the south. The Fenno–Scandian Border Zone has been tectonically active from the Late Carboniferous to the present day and the development of the Rønne Graben, on the western margin of Bornholm, was initiated in the Carboniferous–Permian Time (Vejbæk, 1985).

Precambrian basement, orogenesis and uplift phases
The oldest Precambrian rocks of Bornholm include the foliated and medium-grained Bornholm Gneiss and the medium-grained Paradisbakke Migmatite (Fig. 9), which have been deformed by superimposed folding. Partial melting of it might have been the source of the dark coloured Rønne Granite (Callisen, 1934, Micheelsen, 1961, Gravesen, 2006).

These rocks can be considered as a part of the Svecofennian Orogenic Belt that formed approx. 1600 million years ago. Rocks of a similar age and construction can be traced to Blekinge and Southern Sweden (Berthelsen, 1988, 1989). The basement rocks of Bornholm were not affected thermally by the later Sveconorwegian Orogenic Phase (1100-950 million years ago) as Bornholm and eastern Scania fell outsite this N–S orogenic belt (Berthelsen, 1988).
In a subsequent period, after the Svecofennian Orogenic Phase uplift, faulting and erosion of the basement occurred and the basement was intruded by granitic magma, which includes the light-coloured medium-coarse-grained Vang, the medium-grained Alminding and Hammer Granites and the coarse-grained Svaneke Granite. These granites have been dated to 1255 – 1390 million years ago (Larsen, 1971).

The granites cut the structures of the older basement rocks, the grey Bornholm Gneiss. All the basement rocks are also cut by light red-grey coloured fine-grained aplites and coarse-grained pegmatites. These rocks are considered as formed from the same magma as the Hammer and Alminding Granites (Micheelsen, 1961, Gravesen, 1996).

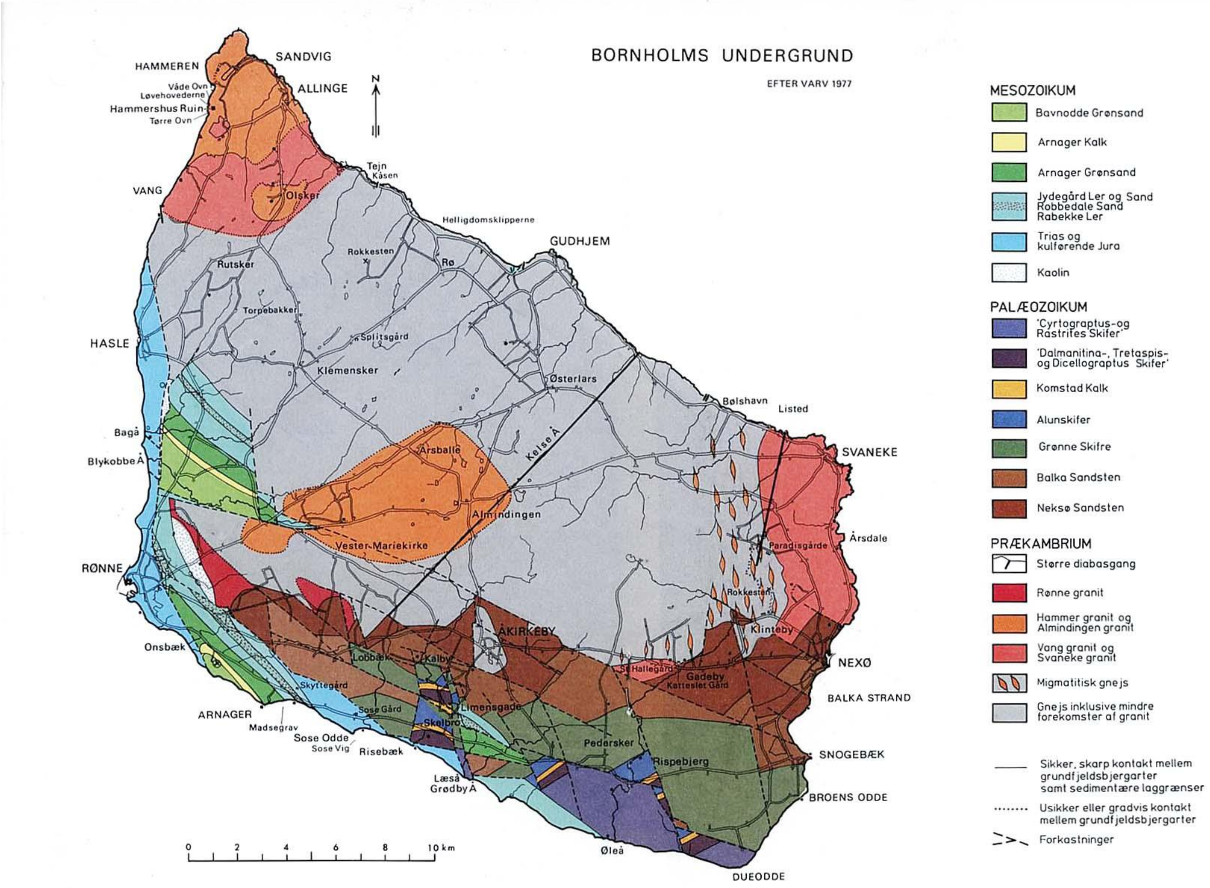

Figure 9. Map of the pre-Quaternary surface of Bornholm (From VARV, 1977).

After cooling and consolidation, the granites were subject to another phase of uplift and faulting. The largest fault zones form rectilinear valleys (Micheelsen, 1961). The valleys were formed during the Weichselian by glaciers that eroded and removed crushed rocks from the fault zones. The dominant fault zones strike N–S and NE–SW but NW–SE orientations also occur. The faults can be followed towards the south under the sedimentary cover. Several generations of basic olivine dolerites (diabases) were intruded into sheared and brecciated fault zones, mainly in N–S or NE–SW directions. The cutting relations of the dykes document the successive intrusive episodes (Noe-Nyegaard, 1963). The dykes are often assumed of Late Precambrian age, but palaeomagnetic studies indicate that some of the dykes may be of Early-Middle Palaeozoic age (Abrahamsen, 1977). Münther (1973) also demonstrated a younger age for some of the dykes, since they penetrate the Palaeozoic sediment cover.

In general, the basement rocks are intersected by numerous fractures, mainly in one horizontal and two vertical fracture sets, but sometimes as oblique fractures. The vertical fractures are oriented NNW–SSE, NNØ–SSW or ESE–WNW. The frequency of the fractures is very variable. The spacing between the fractures can be below one meter, in some areas with up to 15 cm thick vertical zones of cataclastically crushed rock, but in other areas, the spacing can be of 5–10 meter or more. The fractures can be followed to a depth of approx. 50 m in the quarries, but borehole data point to occurrences of fractures and shear zones down to 60-100 meter below surface. It is difficult to separate the basement rocks based on fracture occurrence because of very few investigations (Platou, 1970). The fractures are normally up to 1 mm thick and often with the green mineral chlorite on the fracture surfaces and some of the feldspars are changed to sericite.

During the latter part of the Precambrian, erosion and weathering occurred in the rocks but also during e.g. the Jurassic, parts of the Rønne Granite was transformed to white kaolin because of the warm, moist and rainy climate during that period.

Faults are separating the Precambrian basement from the Mesozoic deposits along the west coast and from the Palaeozoic deposits along a line running NW–SE. Many small fault bounded blocs are located on the southern part of the island.

Palaeozoic Platform deposition and tectonics

Deposition of red fluvial and aeolian sand started in the Early Cambrian. Then gradually the conditions changed to a marine environment where quartz rich sand, often with glauconite, was deposited in the tidal shoreline and shelf areas (Clemmensen & Dam, 1993).

The sedimentation pattern changed in the Middle Cambrian. During the rest of the Cambrian, the Ordovician and the Silurian, the dominant deposits were marine dark organic rich mud and limestone (Pedersen, 1989). There are several hiatuses in the succession pointing to periods of tectonic movements and erosion. The shales and limestones were deposited in an epicontinental sea under low-energy and anoxic conditions (Pedersen, 1989). During Upper Ordovicium and Silurian, bentonites and tuffaceous sand layers are present in the succession indicating volcanic activities. Upper Silurian, Devonian, Carboniferous and Permian deposits are not represented on Bornholm.

Mesozoic basin extension and shoreline deposition

The major hiatus also includes most of the Triassic and corresponds to the period of the late Caledonian Orogeny and the Hercynian Orogeny. The Fenno–Scandian Border Zone was activated several times during the Mesozoic rift phase (Triassic–Jurassic). This rifting resulted in differential subsidence of the Rønne Graben, which in combination with eustatic sea-level variations controlled deposition onshore, as well as offshore Bornholm during this period (Gravesen et al., 1982, Gry, 1969, Nielsen, 2003).

Deposition started in Late Triassic with red and green clays and sands formed on a river plain near the coastline. After a period of block faulting, uplift and erosion, sedimentation began in the Early Jurassic and continued until Middle Jurassic.

This time span was dominated by deposition of yellow and brown sand, clay and coal in deltas, and in shallow tidal and beach areas. Deposition under fully marine conditions also occurred close to a fault-controlled shoreline. The Jurassic succession ended with deposition of clays, coal and sand on a delta plain in channels, levees and

swamps. Conglomerates were re-sedimented into the basin from nearby fault scarps, testifying to tectonic acti-vity in the Middle Jurassic time.
The Middle Jurassic to Early Cretaceous was a new period of faulting, subsidence, uplift and erosion. During the Early Cretaceous, deposition of sand and clay occurred in the shallow shoreline areas: Rivers, coastal swamps, barrier islands, beaches, tidal flats, lagoons, back barriers and wash-over fans (Noe-Nygaard & Surlyk, 1988). The Early Cretaceous sedimentation was strongly influenced by tectonic activity. After a hiatus until Late Early Cretaceous, three episodes of marine transgressions occurred interrupted by periods of non-deposition or erosion. The marine deposits consist of glauconitic fine-grained sand and clayey chalk laid down on the shallow shelf.
Deposits from Late Cretaceous are not known from Bornholm. Probably, the island was uplifted and eroded. In offshore areas, the tectonic history effecting the Rønne Graben, Arnager Bloc and the Risebæk Graven demonstrate a complex series of syn-rift, post-rift and subsidence episodes and basin inversion episodes during the Mesozoic (Grav-ersen, 2004).

Tertiary inversion tectonics
The latest Cretaceous and the Tertiary is a period during which Bornholm was a land area without, or with only local deposition. The period is also dominated by inversion tectonics and transpressional movements replaced the former transtensional move-ments (Gry, 1969). These tectonic movements re-activated faults in the Fenno-Scandian Border Zone where former normal faults became reverse faults. Bornholm and the surrounding areas were partly uplifted and eroded but on small tilted fault blocks, the pre-Quaternary deposits were protected, at least partly, against erosion.

Quaternary glaciations and land movements
Thin Quaternary glacial tills and meltwater sand and gravel cover the basement rocks and the pre-Quaternary deposits but with windows especially in the granite – gneiss area (Grönwall & Milthers, 1913). The deposits are relatively thin over much of the is-land but in the valleys cut into the Precambrian rocks, Quaternary deposits can reach a thickness of 30–50 m. The deposits show no or few sign of glaciotectonic disturbances.
After the melting of the last glacier, Bornholm was first surrounded by a lake and later on by the sea. Erosion and deposition occurred along the coastline and beach terraces and beach deposits were formed. Deposition of gyttja and peat occurred in lakes in the middle part of the island. Tectonic movements in the Holocene resulted in uplift and a slight tilting of Bornholm. Like that, all beach lines are located above the present sea level and the le-vels of the terraces are higher on the northern than on the southern part of the island.

7. THE PRE-QUATERNARY SURFACE

The pre-Quaternary surface, the boundary surface between the pre-Quaternary sediments and rocks and the Quaternary sediments has been developed as a result of deposition, tectonic movements and erosion. The results can be seen by the distribution of the pre-Quaternary sediments (Fig. 10) and by the morphology of the Pre-Quaternary surface (Fig. 11).

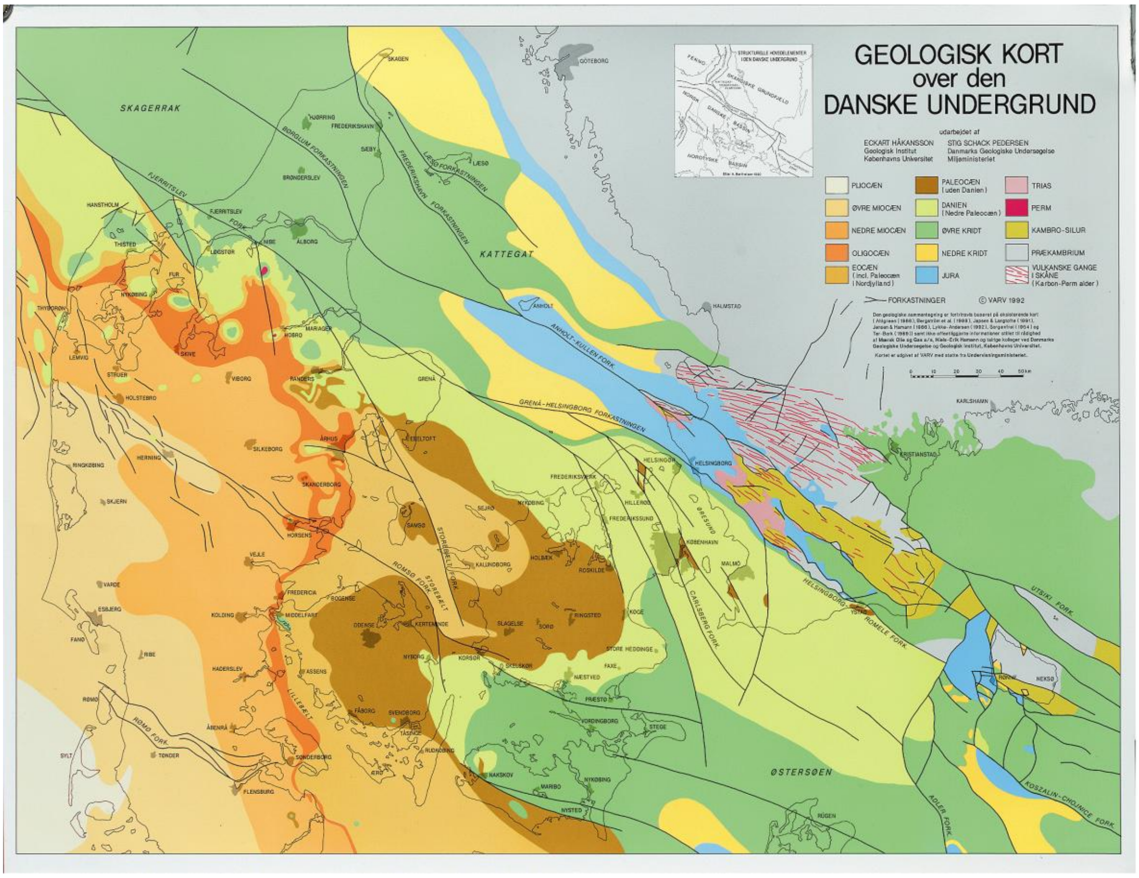

Figure10. Map of the pre-Quaternary surface: Time units. Original scale: 1:50.000. Legend: Red lines: Precambrian intrusions, grey: Precambrian, olive: Cambrian-Silurian, red: Permian, light red: Triassic, blue: Jurassic, yellow: Lower Cretaceous, green: Upper Cretaceous, light green: Danian, brown: Paleocene, yellow olive: Eocene, red brown: Oligocene, light yellow brown: Lower Miocene, very light yellow brown: Upper Miocene, white: Pliocene (Håkansson & Pedersen, 1992).

The features in the pre-Quaternary surface are mainly caused by glacial erosion in the last part of the Pleistocene. Many valleys and low laying areas cut the high-laying area in the middle part of Jylland. Towards the north and the southwest, the depth to the surface exceeds more than 250 m below present sea surface. In these areas, marine successions were deposited during Holsteinian, Eemian and Weichselian and the sedimentation prevailed throughout the Holocene with accumulation of fresh-water and marine deposits. The valley systems were eroded out as tunnel valleys below the large glaciers. However, in many cases the valleys were originally initiated as pre-Quaternary tectonic features as e.g. the graben structure in the Horsens valley (Lykke-Andersen, 1979, 1995).

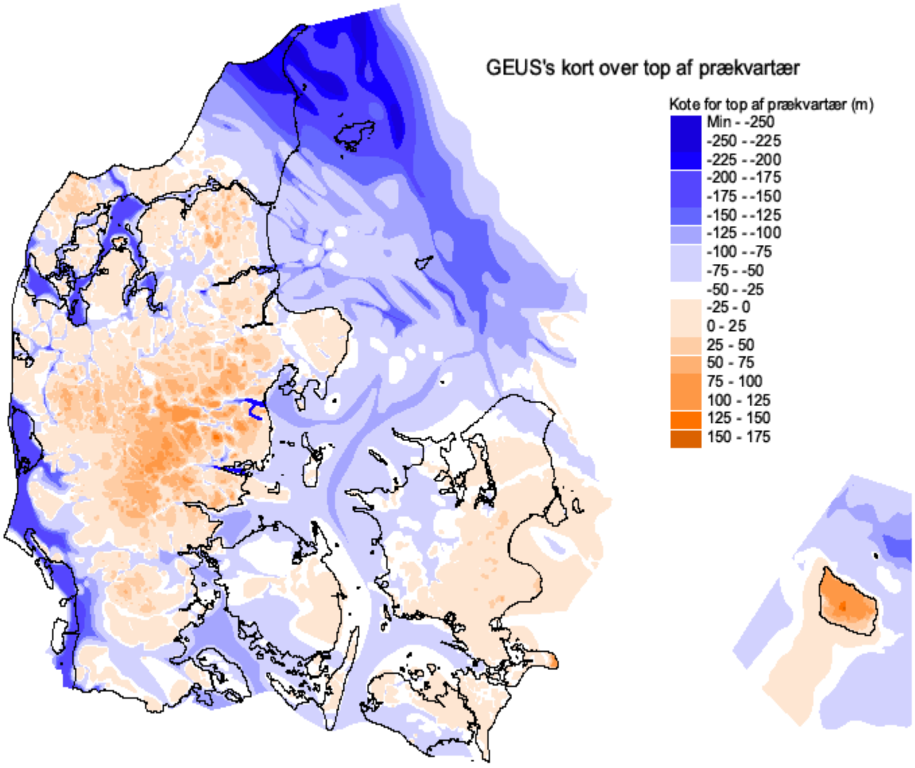

Figure 11. Map of the elevation of the pre-Quaternary surface (From Binzer & Stockmarr, 1994). Legend: Contours intervals for the elevation in meters. Deepest elevation in blue colours (-50 m to below -250 m). Highest elevation in white, yellow and orange colours (-50 m to + 175 m).

The difference between the topographic map (Fig. 1) and the pre-Quaternary surface elevation map (Fig. 11) gives the thickness of the Quaternary deposits (Fig. 12).

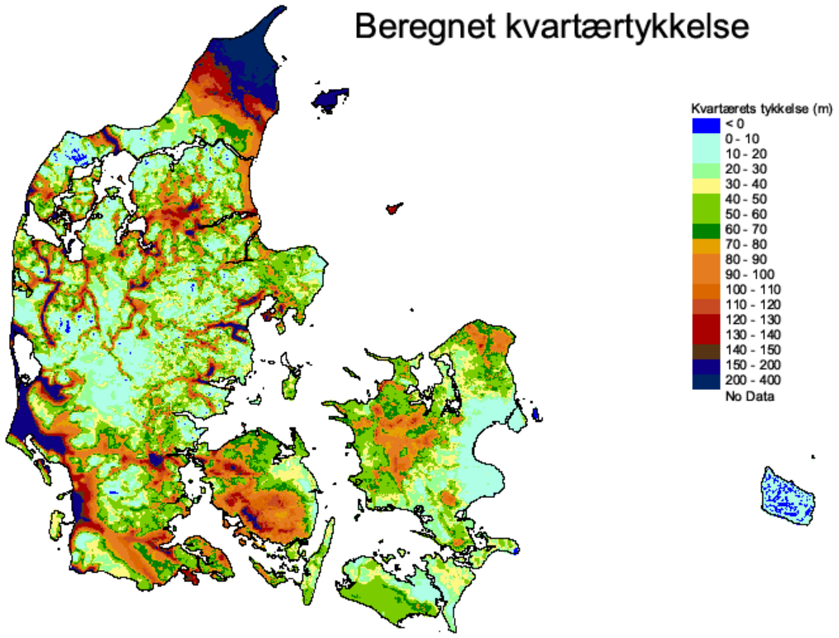

Figure 12. Map of the thickness of the Quaternary sediments (Frants Von Platen, GEUS, 2008). Legend: Contour intervals for thickness in meters. Green colours for thinnest thicknesses (from 0 m up to 70 m) orange colours for middle thicknesses (70-120 m) and brown and blue colours for largest thicknesses (120-400 m).

Detail-studies using geophysical surveys and borehole data can give a more complex picture of the distribution of the deposits and the fault pattern (Fig. 13). The example from Sjælland is based on many boreholes from which it is relatively easy to recognize the age of the sediments. The map displayed in Fig. 13 is very different from the maps in Fig. 2 and 10, which demonstrates the expected difference between the regional and local maps.

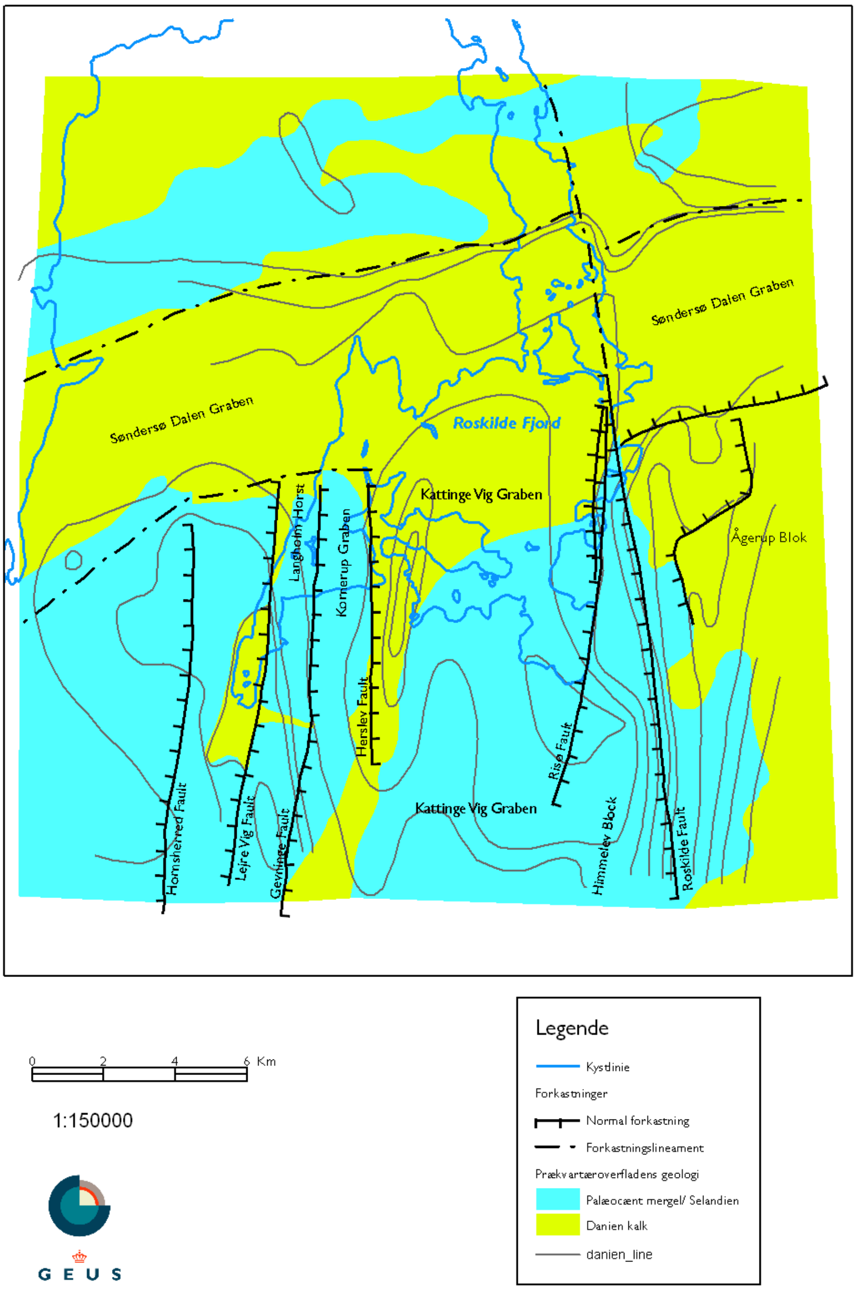

Figure 13. Map of the pre-Quaternary surface in the Roskilde Fjord area (From Gravesen & Pedersen, 2005). Several faults and graben systems are recognized. Legend: Green: Danian limestone, Blue: Selandian clay and limestone, thick black lines: Faults.

In addition to the mentioned maps, other thematic maps showing parts of the pre-Quaternary surface and the structures have been constructed. Among these thematic maps, the Structural Map of the Top Chalk Group (Ter-Borch, 1991) can be mentioned. Structures in the chalk, formerly described as faults or folds, seems in some cases to be syn-sedimentary topographic features as mounds and channels on the sea bottom in the Late Maastrichtian (Surlyk et al., 2006, Surlyk et al., 2010).

8. GLACIOTECTONICS AND GLACIAL STRUCTURES

8.1 Major structures

The structural geology of surface-near deposits in Denmark is strongly influenced by glaciotectonic deformation. All of Denmark was covered by glaciation in the Saalian time about 300.000 years BP, and glaciotectonic structures formed during this glaciation are well known from western Jylland. In the Weichselian, the Main Stationary Line of the Scandinavian Ice Cap was located in the northern and central part of Jylland (Fig.14). Therefore, all of Denmark has been affected by glacial deformation, and in many places, the bedrocks have been displaced by glaciotectonic actions. Along the Danish coastline, a number of beautifully exposed cross sections display instructive examples of the glaciotectonic deformation (Figs. 15 and 16).

No or very few deformations of the sediments on Bornholm have been recognized until now but the basement rocks have suffered glacier erosion and deformation. Roche moutonnes and other marks in the rocks together with abundant horizontal fractures are the most significant glaciogeological fractures.

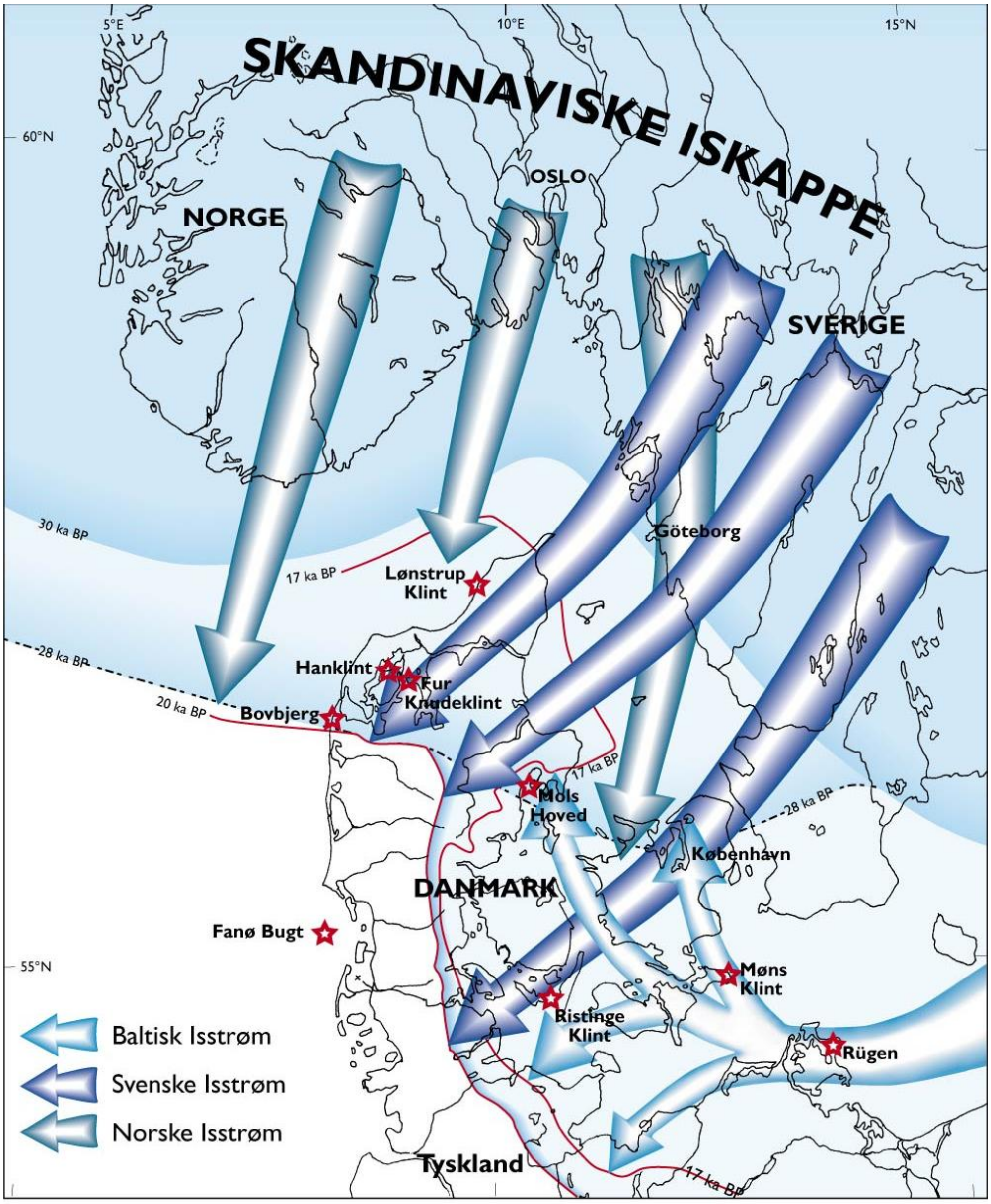

Figure 14. The glacier advances during the Weichselian. Red asterisks mark Glaciotectonic complexes in Denmark.

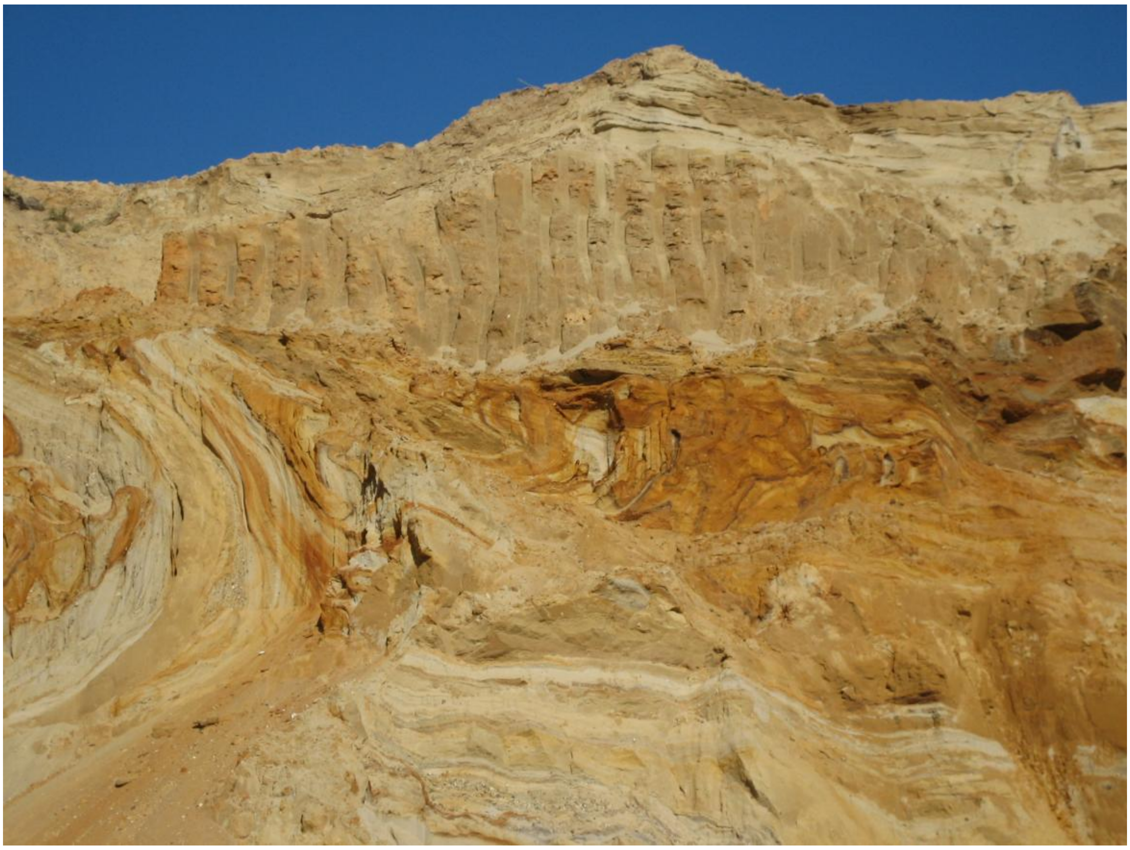

Figure 15. An example of glaciotectonic deformation in the Saalian landscape. Attenager, map sheet Ringkøbing.

Figure 16. An example of Weichselian glaciotectonic deformation, the Hanklit thrust sheet on northern Mors. This thrust sheet comprises Eocene diatomaceous clay with volcanic ash layers, and it was displaced c. 300 m over Pleistocene outwash deposits.

In general, the glaciotectonic deformations created folds and thrust fault structures. In very clay-rich and muddy lithologies, mud diapirs may have formed (Pedersen, 2005). Often, the structures can be mapped out to be grouped in a complex with a hinterland part, a central part and a foreland part. The complexes vary in size from a few hundred meters in cross section and along strike to larger complexes covering areas more than 25 km^2 in size. The larges complex mapped is recognized in a cross section extending 6 km from south to north (the Rubjerg Knude Complex, Pedersen, 2005), and the longest fold structure in mo clay and volcanic ash layers can be traced for 10 km along the fold axis (Klint & Pedersen 1995) (Fig. 16). The general depth of glaciotectonic deformation has been estimated to be about 100 m below surface (Pedersen ,1996, 2005), and hills reaching an elevation of 130 m above sea level is known from e.g. the Møns Klint (Pedersen, 2000). The Møns Klint glaciotectonic complex comprises displaced Maastrichtian chalk, which is the oldest bed-rock known to be affected by glaciotectonics in Denmark. This complex as well as a majority of glaciotectonic complexes form a parallel-ridges landscape that mirrors the imbrications of thrust sheets in the subsurface, typically with the development of hanging-wall anticlines on the crest of the thrust sheets (Fig. 17).

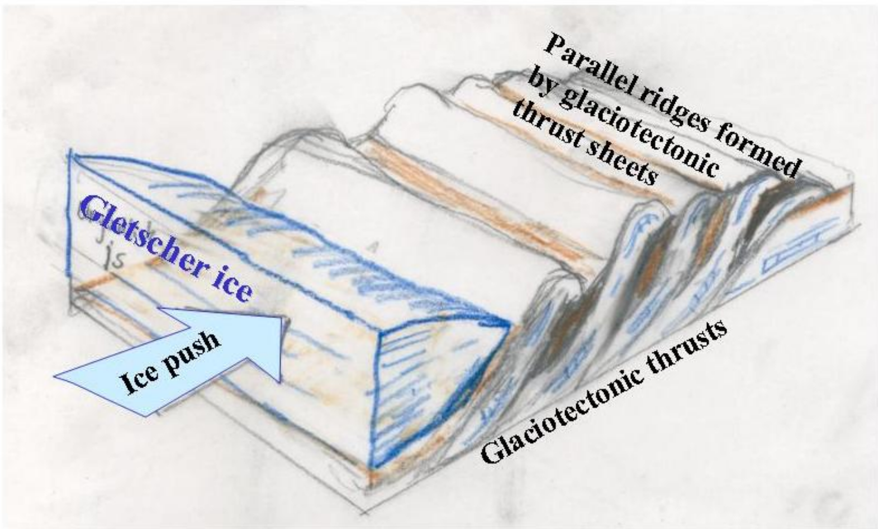

Figure 17. Principle sketch of a glaciotectonic complex. The glaciotectonic thrust faulting creates a landscape with parallel ridges perpendicular to the direction of the ice push. The thickness of the thrust sheets are in the order of 50 m, the crests are elevated up to 100 m above the primary depositional position of the layers. Along strike, the length of the crests can be up to 10 km.

The glaciotectonic deformations and disturbances of the shallow pre-Quaternary and Quaternary deposits are also demonstrated by borehole data as described by Jakobsen (1996), where floes and sediment sheets of the pre-Quaternary and interglacial sediments can be found in the borehole logs (Fig.18). The information is based on borehole data from GEUS´ Jupiter Database where descriptions, characterizations and dating of sediment samples are stored (Larsen et al., 1992). Many borehole logs are mapped in the Geological Basic Data Maps, which are produced for a large part of Denmark (e.g. Gravesen, 1993, Hansen, 1994, Jakobsen, 1993). (See also Gravesen et al., 2010).

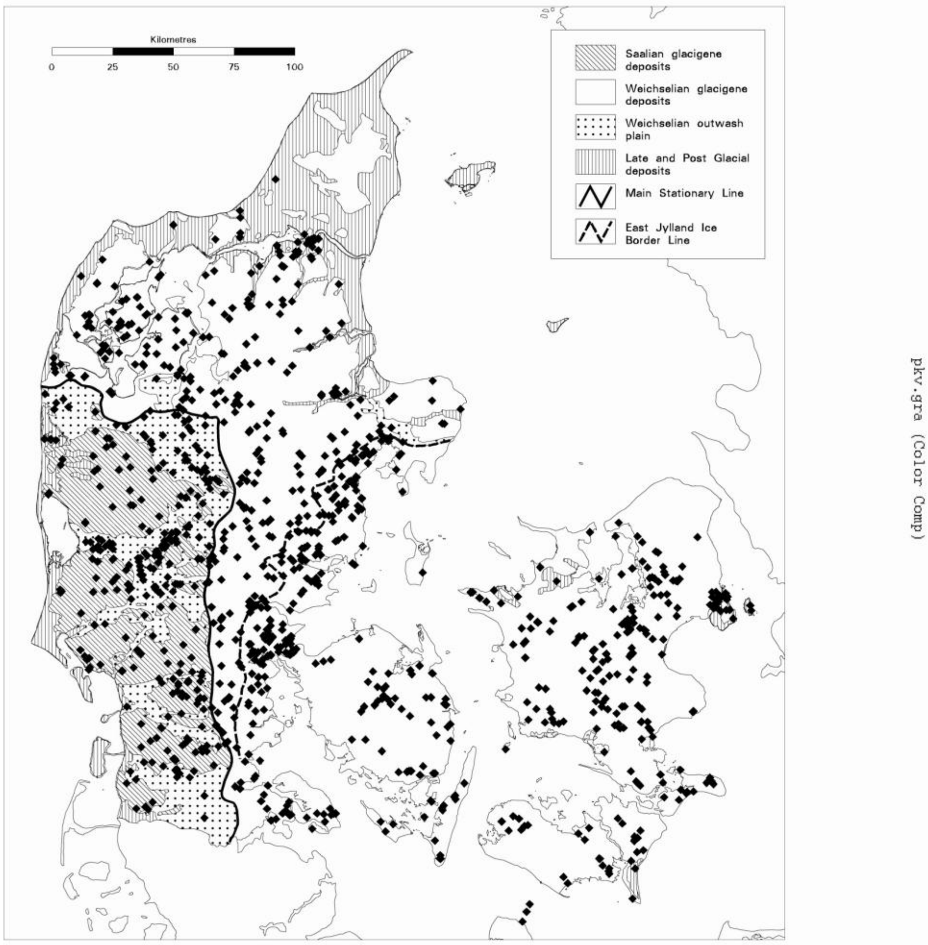

Figure 18. Distribution of boreholes with borehole logs in which dislocated pre-Quaternary sediments are recorded above or between Quaternary deposits (From Jakobsen, 1996).

8.2 Fractures and joints

Sediments and rocks are often cut by fractures of which many are of tectonic origin. The basement rocks of Bornholm are cut by several generations of joints and fractures, which may be related to succeeding tectonic events (Gravesen, 2006) (Fig. 19).

The fractures are not only formed by major tectonic events but also by the deformations related to advances of the Quaternary glaciers.

Figure 19. Strongly fractured Precambrian Hammer Granite from northern Bornholm, Denmark.

The main part of the Danish limestone and chalk deposits are affected by fracturing. There seem to be a tendency of random glaciotectonic fracturing superimposed on Paleogene wrench related fractures (Jakobsen et al., 2002). However, the distribution of fractures varies a lot from locality to locality and is highly dependent on the lithological behavior (Fig. 20). The fractures are oriented vertical and horizontal but many top layers of the limestones and chalks have been crushed and fractured by glaciers (Jakobsen et al., 2002).

Figure 20. Danian limestone cut by horizontal and vertical fractures.

Mesozoic, Paleogene and Neogene fine-grained and plastic clays often contain tectonic fractures. Moreover, thaw-freeze fractures can be found in the top layers. In many clay types, the combination of fractures and heavy rain followed by dry conditions can give stability problems (Gravesen et al., 2010).
Clayey tills are normally fractured within the upper 10 m below ground surface where e.g. the conjugating sub-vertical fracture sets are considered as tectonic (Klint & Gra-

vesen, 1994) (Fig. 21). Other macropores are formed by biopores: Rootlets and earth worm burrows (Fig. 21).

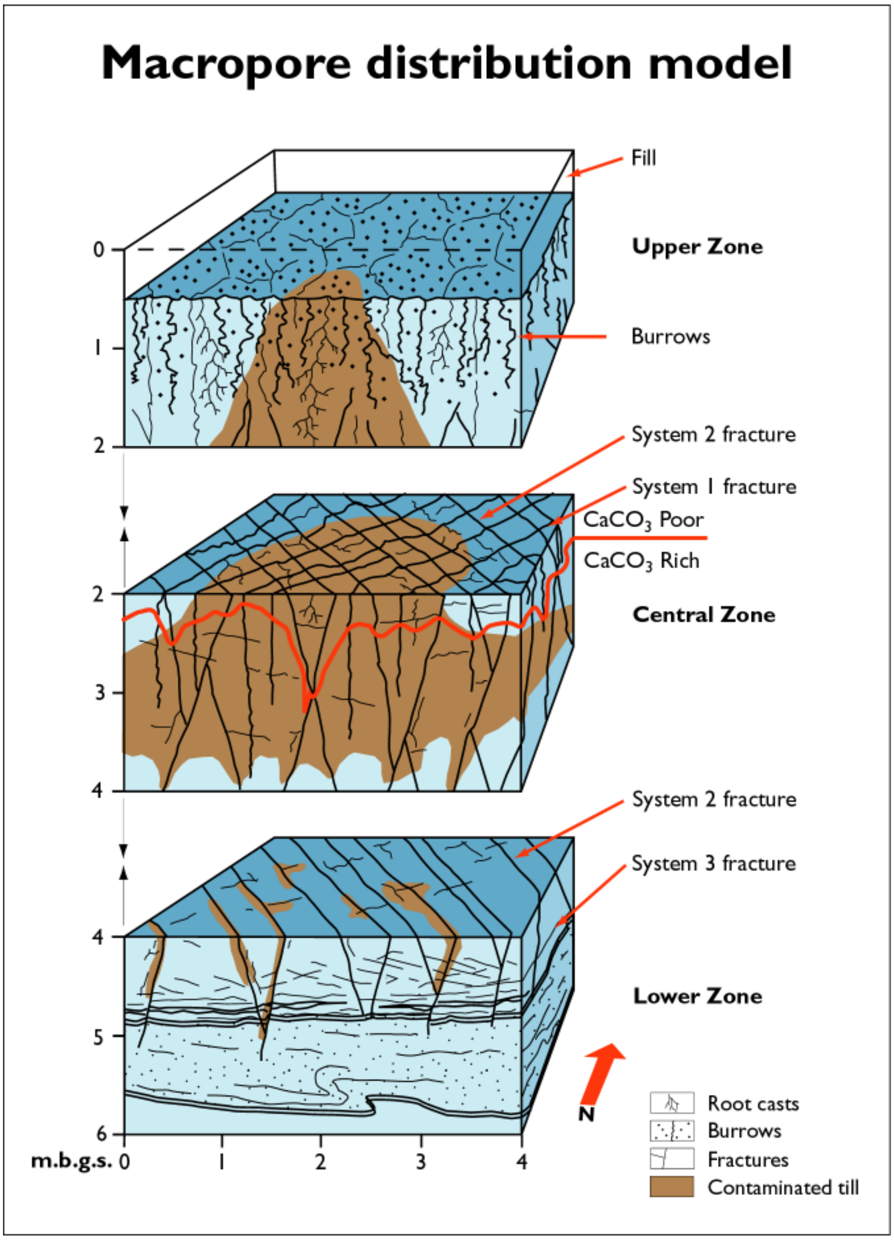

Figure 21. Model of the macropore/fracture systems in clayey tills (From Klint & Gravesen, 1994).

The fractures in clayey tills have been studied especially during the last 20 years from a series of sections in coastal cliffs and pits (Fig. 22).

Figure 22. Clayey till profile from a gravel pit, Sjælland. Sets of sub-vertical fractures can clearly be recognized (Photo: K.E.S. Klint).

The vertical and sub-vertical fractures in sediments and rocks transport surface water from the ground surface to the groundwater. Horizontal fractures can transport the water long distances away. If the water contain pollution components these could be distributed over large areas.

8.3 Buried valleys

Abundant geophysical surveys have recently discovered systems of buried valleys in the Quaternary sediments and occasionally also cut down into the pre-Quaternary sediments (Jørgensen & Sandersen, 2009)(Fig.23) The age of the valleys can be difficult to determine but the Elsterian, Saalian or Weichselian ice ages are possible time for the formation.

Figure 23. Mapped buried valleys in Denmark (From Jørgensen & Sandersen, 2009).

9. LATE AND POST GLACIAL ELEVATION AND HOLOCENE SUBSIDENCE

9.1 Late glacial – Late Weichselian elevation

When the last glacier from the Late Weichselian melted away from the Danish territory, the unloading of the area gave way to an isostatic rise of the land. Subsequent, the sea level was raised because of the huge amount of melt water from the glaciers and during a long period especially the northern Denmark was covered by a cold ice sea. The net result of the land elevation and sea level rise has produced a rise of coastal cliffs now found up to 60 m above present sea level in northern Denmark. The high is decreasing southwards in Jylland to 5 m above present sea level at Mariager Fjord (Fig. 24).

9.2 Post glacial – Holocene elevation and subsidence

During the Holocene, periods of transgressions and land elevations have interacted (e.g. the Littorina transgressions). The elevation of fossil coastal cliffs is well known from the northern half of Denmark with a maximum elevation of up to 15 m in the NW Vendsyssel (Mertz, 1924). Along the north coast of Sjælland, the elevation is about 10 m above present sea level decreasing southwards to 0 m in southern Sjælland, mid Fyn and Ringkøbing Fjord (Fig. 25). South of the Ringkøbing–Fyn High, the land surface has subsided more than 4 m (Pedersen & Rasmussen, 2000).

Fig. 24. Isobases for the coastlines from the Late Weichselian ice sea (red contours) and the Holocene Littorina sea (blue contours) (From Mertz, 1924).

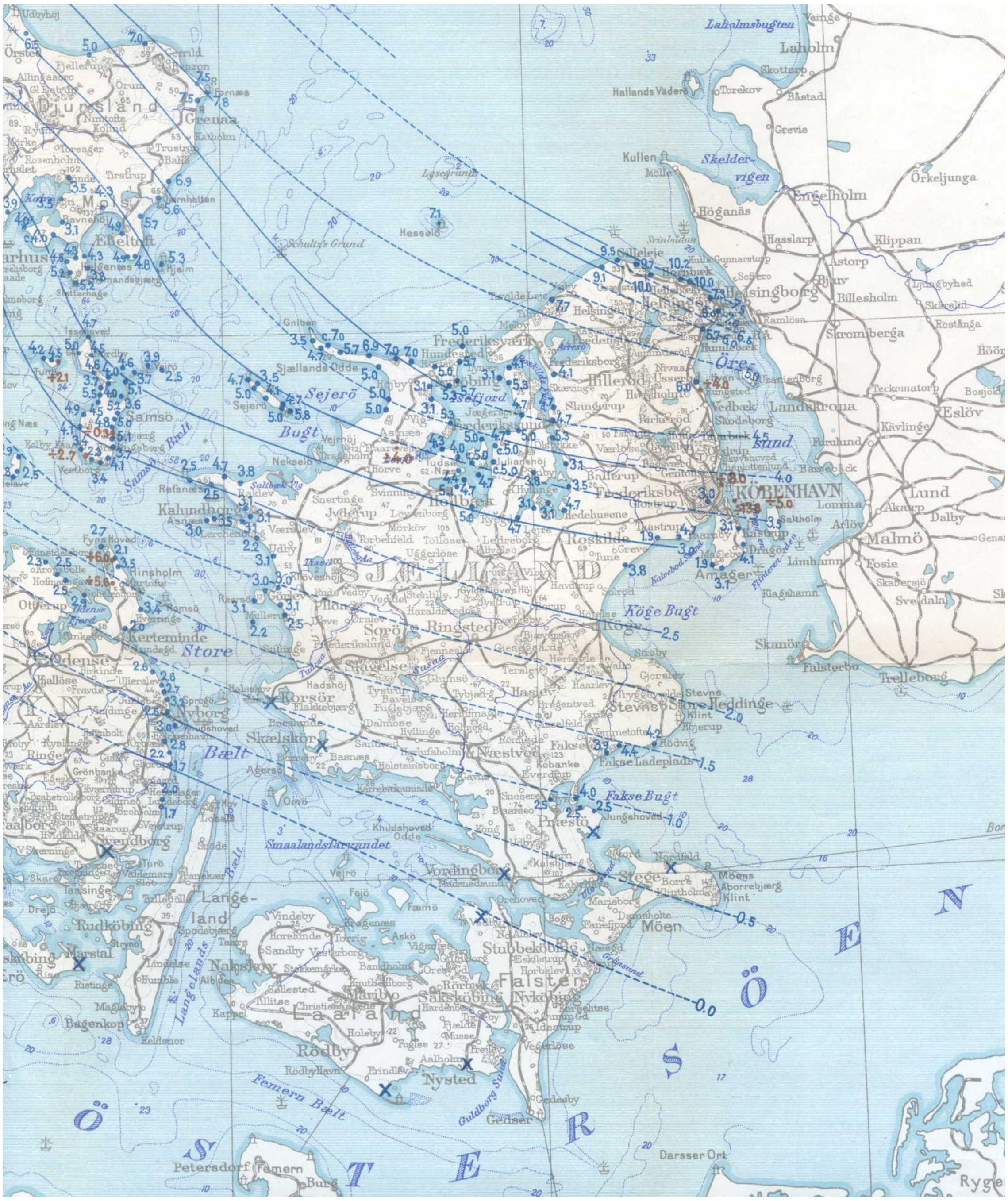

Figure 25. Isobases for the coastlines from Holocene Littorina sea (Blue contours) (From Mertz, 1924).

10. RECENT MOVEMENTS, LANDSLIDES AND EROSION

10.1 Glacio-isostacy and sea level rise

The recent movements of the Danish land area are guided by the last glacio-isostatic rebound succeeding the melting of the Scandinavian Ice Cap at the termination of the Weichselian glaciations. The glacio-isostatic elevation is interpreted to have inherited deep-seated tectonic faults by adjustment faults. The recent relative vertical movements are very small and according to the measurements of the National Survey and Cadastre (KMS) 1884-1992 (Knudsen & Vognsen, 2010), an uplift of the land area of up to 0.5 mm/year occur in northern Jylland and northern Sjælland, while a subsidence of up to 1.0 mm/year occur in southern Denmark. The absolute uplift in Denmark has been positive with 2 mm/year at Hirtshals to approx 0.5 mm per year at Esbjerg in the period 1990-2000. The recent average absolute sea level rise has been approx. 3 mm/year in the period 1990-2006 which is an increase of the rate of 1.5 mm/year in the period 1900-2008 (Knudsen & Vognsen, 2010).

10.2 Landslides

Landslides are very common along the coastal cliffs dominated by clayey lithologies (Fig. 26).
Moreover, cliff collapses with dramatic rock falls occur periodically at coastal cliffs, where Upper Cretaceous chalk or Danian limestone are exposed. The most hazardous cliff collapses occur along Møns Klint (Fig. 27) where a person was killed 15 years ago. The major cliff collapses have a frequency of one per each 3–5 years and the last major rock fall appeared in January 2007 (Pedersen & Gravesen, 2009) (Fig. 27). At this rock fall, a huge amount of chalk material at St. Taler established a large new coastal area.

The reasons for the landslides are the weather conditions with changing precipitation and freeze and thaw processes.

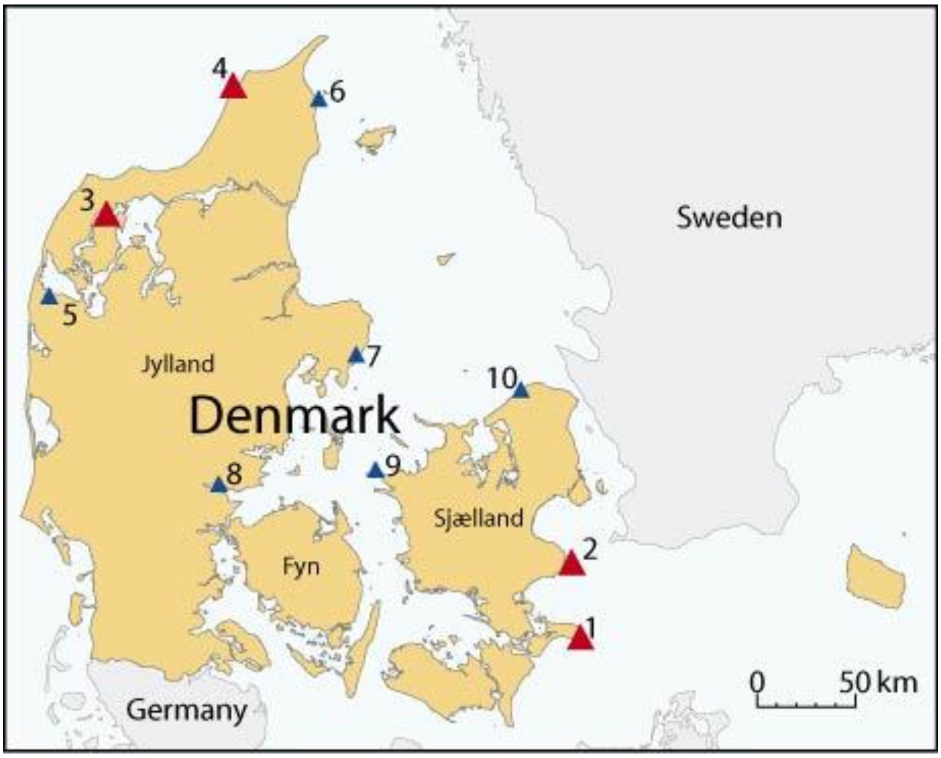

Figure 26. Map of landslide geohazard areas in Denmark. Legend: Red triangles: High-risk areas, Blue triangles: Low-risk areas (From Nadim et al., 2008).

Figure 27. Example of landslide at Møns Klint: the St. Taler slide January 2007. More than 100.000 m^3 were displaced for a distance of up to 300 m from the coast.

The general landslide hazards in clayey lithologies are not very dramatic. The structural model of the main landslides and their mechanic development is illustrated in Fig. 28

and the typical terrace morphology of coastal areas affected by landslides is shown in Fig. 29.

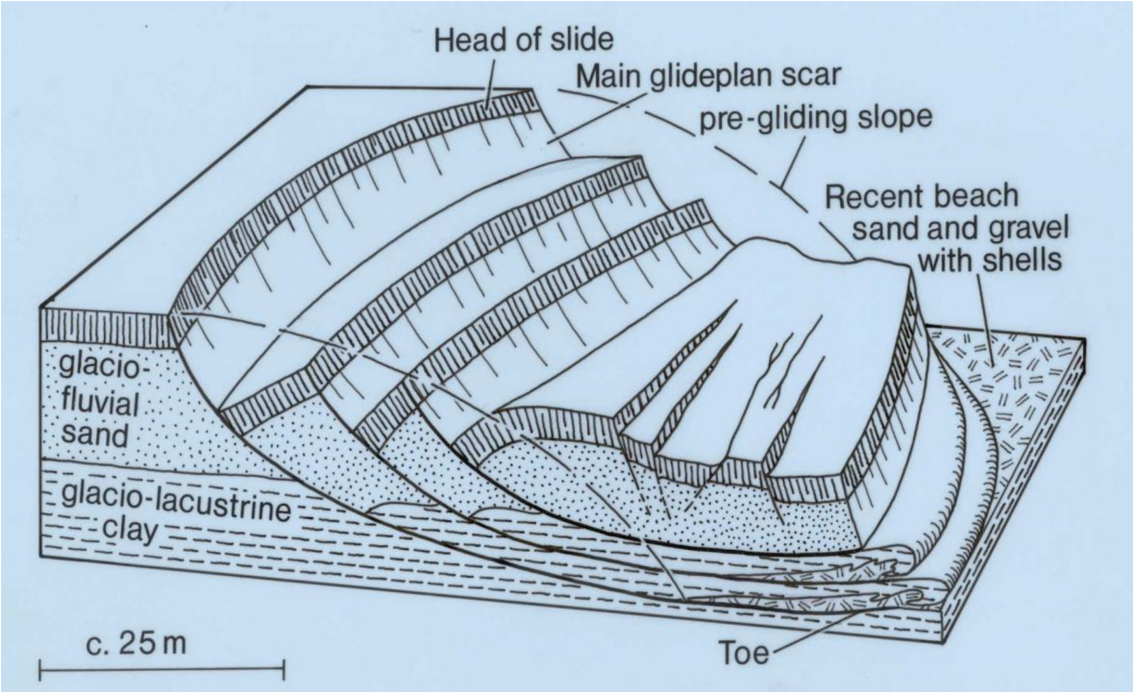

Figure 28. A structural model for landslide developing (From Pedersen, 1987).

Figure 29. Example of normal extensional imbrications of the head of a landslide from Sundby Bakker, Mors. The displace along each escarpment was approx. 1 m/year and the sliding lithology constitutes Paleogene plastic clay.

11. SEISMIC ACTIVITY DURING THE LAST 150 YEARS

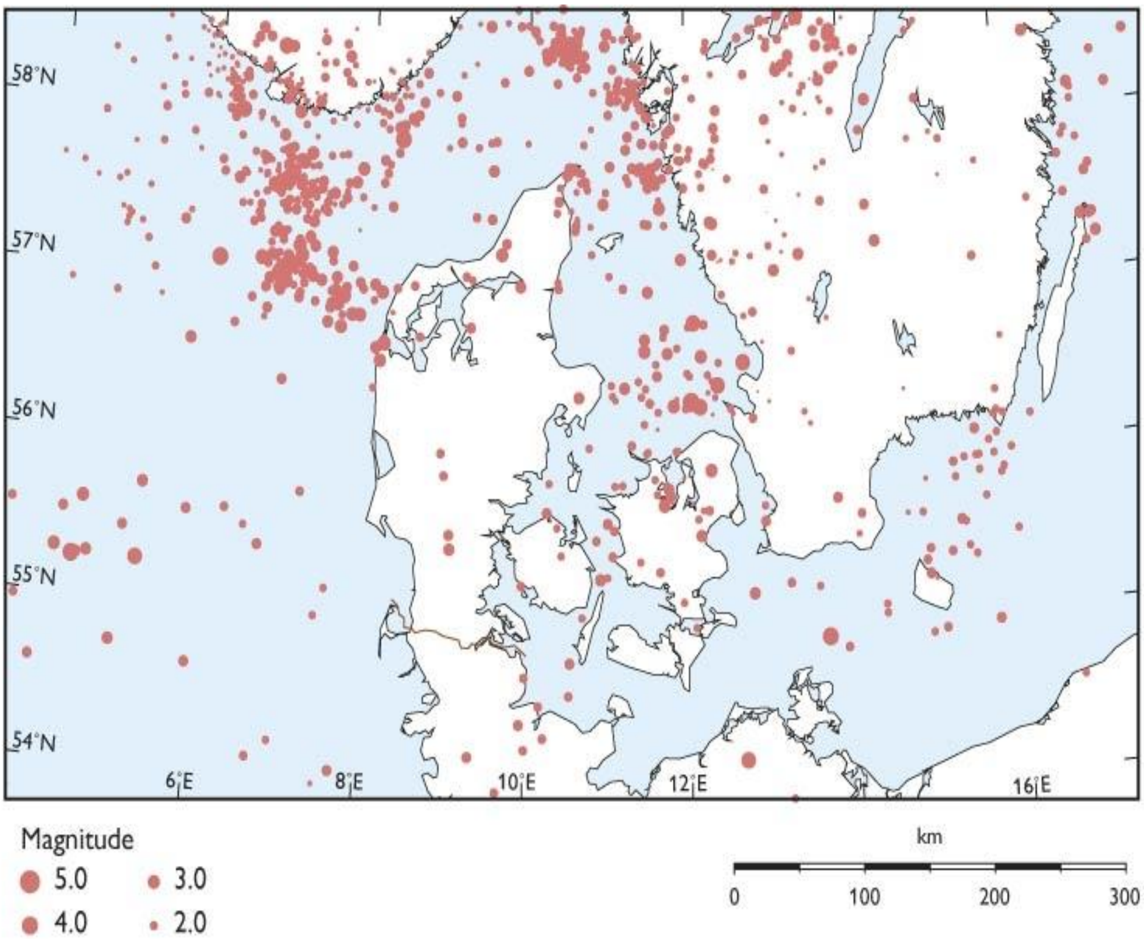

Figure 30. Seismicity in Denmark and surroundings 1970 to 2008. Epicentres are from GEUS earthquake catalogue and Catalogue of earthquakes in Northern Europe by University of Helsinki. All epicentres are determined using a minimum of three stations (After Larsen et al., 2008).

Seismic activity in Denmark is weak and uneven located as seen in Fig. 32. Generally, the level of earthquakes in Denmark is between 1.5 and 4.5 on the Richter scale (Gregersen et al., 1998, Larsen et al., 2008). Large areas are free of earthquake activity. These may be interpreted as sustainable blocks. Seismic activity has been registered back to 1677 (with some indications of events as early as 1073) as written communications (Abrahamsen, 1967). The most active earthquake area is the Fenno-Scandian Border Zone, which is the old tectonic zone emplaced in the Palaeozoic Era. Other areas are the North Sea, Kattegat and northern Sjælland around Roskilde Fjord (Gregersen et al., 2005, Voss, 2009).

The correlation of registered earthquake activities to known shallow or deep-seated fault zones is not straightforward. In general, there is no direct indication of seismic activity located along recognized and mapped faults and fault zones in Denmark. One reason for this is of cause that the earthquake focus points are situated in several kilometres depth, whereas the faults are line traces on the surface (or pre-Quaternary surface). However, abundant seismic activity in an area of many faults as in the Roskilde Fjord fault zone area may indicate a certain relationship (Larsen et al., 2008). Also in some parts of the Fenno-Scandian Border Zone it has been indicated that a relationship between location of earthquakes and faults in the in the Sorgenfrei–Tornquist zone occurs (Gregersen, et al., 1996).

12. NEOTECTONIC FEATURES

Neotectonic features are tectonic structures penetrating the Neogene deposits and even the Quaternary sediments, and these structures are activated within the latest 10 million years, typically as initiated movements along the old faults.
In Denmark, few examples of neotectonic activities are proved. Some of them are commented below.

At Hvorslev in Jylland, some fault lineaments and fracture valleys have been related to neotectonic activity in the Weichselian (Jakobsen & Pedersen, 2009) (Fig. 31). It was formerly discussed whether they were tectonic lineaments or features formed during the glaciations. Meanwhile, the correlation of lineaments and fault lines interpreted on seismic profiles supports the tectonic origin.

At Thisted, Jylland, around and above the deep-seated Thisted salt dome, neotectonic elevation movements have taking place during the last 4000 years (Hansen & Håkansson, 1980).

In Kattegat, the Late Weichselian clayey sediments have been displaced along old fault lines. The marine clayey sediments may be correlated with the approx. 15.000-year-old Vendsyssel Formation, which was deposited during the late glacial eustatic sea level rise. At the end of the Weichselian, the glacio-isostatic elevation resulted in reactivation of the fault systems in Kattegat along the Fenno-Scandian Border Zone (Jensen et al., 2002).

Finally, a well-dated neotectonic displacement is recorded above the Børglum Fault Zone on the west coast of Vendsyssel. Here, the 15–17.000 year old deposits in the Vendsyssel Formation were displaced by an approx. 25 m vertical separation before the bog sediments truncated the structure in the Allerød time (c. 12.000 year BP) (Lykke-Andersen, 1992).

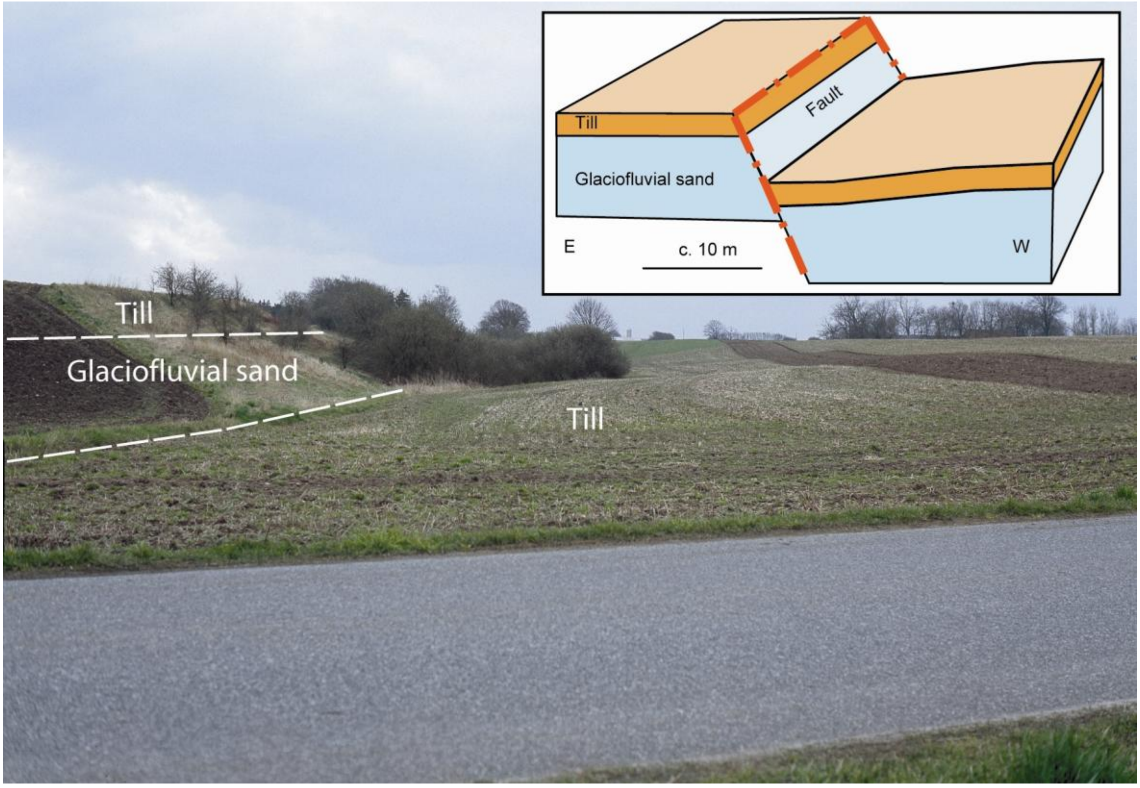

Figure 31. Neotectonic fault line at Hvorslev (From Jakobsen & Pedersen, 2009). The top till and the underlying Quaternary sediments are down thrown to the west with a displacement of approx. 8 m.

13. FINAL REMARKS

The tectonic features of Denmark, deep seated as well as shallow, are very important elements for the understanding of the geological framework. Together with the knowledge of the low permeable and fractured sediments and rocks (Gravesen et al., 2010) they form the background for assessment and selection of potential waste disposal areas. In relation to this selection process, it is important to avoid areas with documented faults and fractures – features that could be a potential danger for movements of the disposal. Especially areas with high risk for recent landslide and neotectonic activities should be avoided. In many countries, detailed investigation of the structural conditions have been performed, mainly by geophysical surveys in combination with boreholes, because these structures are of crucial importance for the location of the disposal (e.g. Juhlin & Stephens, 2006, Milnes, et al., 2008, Wemaere et al., 2008).
The brief description provided in this report gives a basic documentation of the structural features, which have to be considered in the assessment and selection of potential waste disposal areas.

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