DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/38

Geology of the Jammerbugt area

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

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The geological setting of the Jammerbugt area
in the south-western part of Vendsyssel,
northern Denmark

Prepared for Vattenfall A/S, June 2009

Stig A. Schack Pedersen

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GEUS

Introduction

The Jammerbugt is the large bay northwest of Jutland, Denmark (Fig. 1). The name may refer to the lament (“jammer” in Danish) from shipwrecked sailors. Geologists may ask why the coastline changes direction at Hanstholm. The main reason for this is that the bedrock at Hanstholm comprises mounded chalk with chert bands, which is relatively resistant to marine erosion, whereas the bay northeast of Hanstholm is situated in a tectonic depression, which comprises soft clays of Palaeogene age. However, the chalk reappears in the chalk cliff Bullbjerg and further east along the fossil coastal cliff at Svinkløv in the inner part of the Jammerbugt bay. The SE–NW trending lineaments in the landscape indicate that the E–W trending southern coastline of the bay mirror the southwestern boundary of the Sorgenfrei-Tornquist wrench fault zone in the subsurface.

The aim of this report is to describe the significance of this geological setting focusing on the geological history and dynamic development in the Jammerbugt area. The report is prepared for the Vattenfall A/S in relation to the activities concerning location of reservoirs for CO_2 storage in the subsurface of this part of north-western Denmark.

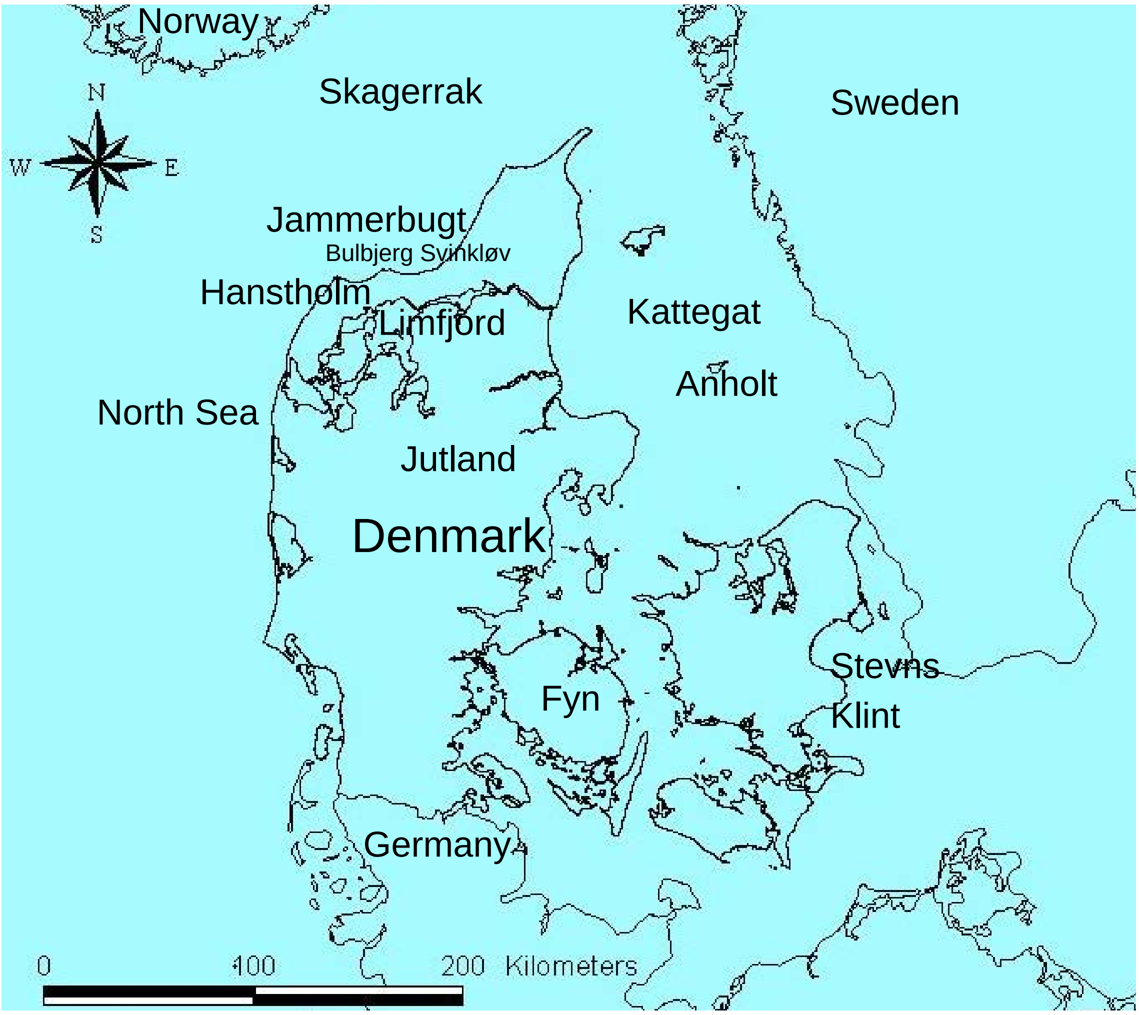

Figure 1. *Map of Denmark with location of names mentioned in the text.*

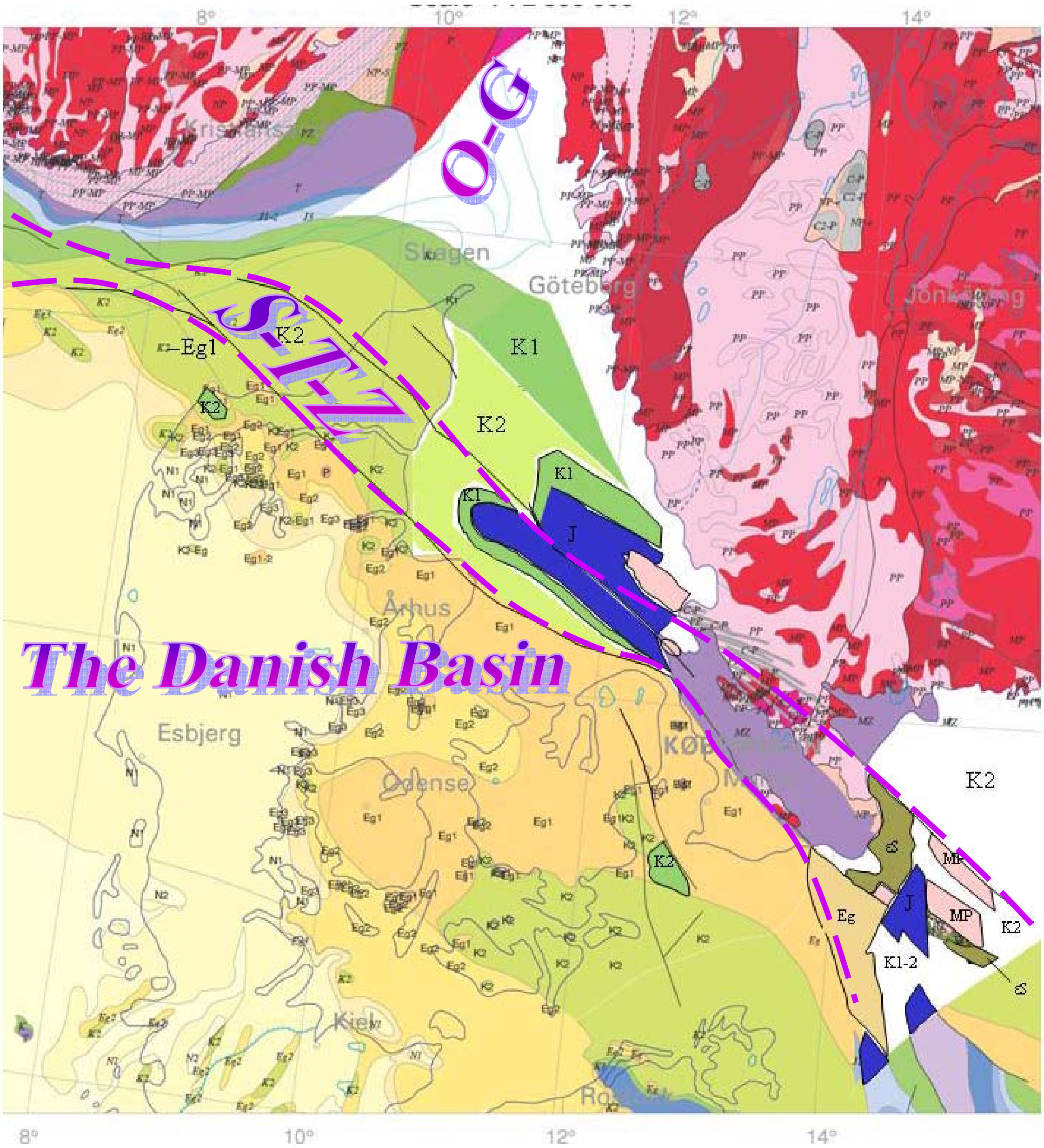

Figure 2*.* *Geological map of the bedrock geology of the Danish Basin. To the north and east the basin is bounded by the Precambrian basement in Norway and Sweden. The red colours on the map represent gneisses and granites of Proterozoic age about 1500 mill. years old. The violet and blue colours indicate Triassic and Jurassic sedimentary rocks. The dark and light green colours are lower and upper Cretaceous chalk, the darker green (K1) with intercalations of lower Cretaceous greensand. The light orange colour represents the Danian limestone, mainly consisting mounded bryozoan limestone interbedded with chert-beds. The boundary between the Cretaceous chalk and the Danian limestone is dated to 65 mill. years. The lighter beige colours indicate the distribution of Tertiary clay and sand with the dominance of Miocene deposits building out towards the North Sea Basin. Part of the Miocene deposits form deltaic settings with lignite beds. The Sorgenfrei-Tornquist Zone (S-T-Z) is a SE–NW trending wrench fault zone, which cross cut the north-eastern part of the Danish Basin. Along this zone substantial displacement took place about 60–50 mill. years ago contemporaneously with the Alpine orogenesis in southern Europe. The Permian Oslo Graben is indicated with O-G.*

Geological setting of Denmark

The geological setting of bed rock geology of Denmark is illustrated on the geological map Fig. 2. It is here seen that the Danish Basin is bounded to the north and east by the Precambrian basement in Norway and Sweden. The basement rocks comprises gneisses and granites of Proterozoic age, which were affected by orogenic tectonics about 1500–1200 mill. years ago. An exception from this is the Oslo Graben, in which the Oslo Fjord is situated. In the graben depression Palaeozoic sedimentary rocks and Permian volcanic rocks (c. 260 mill. years old) have been preserved. Along the western boundary of the graben, granitic and syenitic intrusives related to the same igneous province crop out. Indicator boulders from the Oslo Graben occur abundantly in the Quaternary deposits in northern Jutland, in particular the rhomb porphyry and the Larvikite syenite.

Seismic studies of the Danish Basin often use the Late Permian evaporates as the lowermost reflection and the older deposits are not known in detail. In the main part of the Danish Basin the Zechstein evaporates are overlain by a very thick succession of Triassic sandstones. Their thicknesses vary from 1 to 5 km and the sediments comprise fluvial and lacustrine sediments deposited in an arid environment. From Late Triassic times the Permian evaporites were affected by salt tectonics, and salt diapirs continued to grow during the Tertiary. Quaternary movements of the salt diapirs have been the subject of discussion among Danish geologists. The salt tectonics dominates in the western Limfjord Region, where it contributes to the elevation of the Cretaceous chalk in the Hanstholm area. In the central part of the Danish Basin the salt tectonics is absent, which coincides with the position of the E–W trending basement high known as the Ringkøbing-Fyn High. In the central part of the island Fyn the basement surface is only 800 m below surface. On the south slope of the basement high salt tectonics appears again, and in southern Jutland the salt diapir occurrences continuer into the North Germany Salt Province.

A dominant part of the bedrock geology in Denmark comprises chalk and limestone, in general referred to as the Chalk Group, which comprises the upper Cretaceous chalk and the Danian limestone (Vejbæk 1997) (Fig. 2). The fameous Cretaceous-Tertiary boundary is beautifully exposed along the Stevns Klint cliff section (eastern Denmark), where the uppermost beds of the Maastrichtian chalk are discordantly overlain by the Danian bryozoan mound limestone (Fig. 3). In northern Jutland the Danian limestone is exposed at Hanstholm and in the coastal cliff at Bulbjerg.

The structural geology in the Danish Basin is strongly influenced by SE–NW trending Sorgenfrei-Tornquist Zone (Vejbæk 1997). The zone is a wrench-fault tectonic belt, which is bounded by the Fjerritslev Fault to the southwest and the Børglum Fault to the northeast (Håkansson & Pedersen 1992). In the central part of Kattegat inversion in the wrench-fault zone resulted in uplift of Jurassic and lower Cretaceous successions around the island of Anholt (Fig. 2). The inversion is also recognised in Scania and on the island Bornholm.

In a geotectonic framework the Danish Basin form the eastern part of the intracontinental North Sea Basin that throughout the Cainozoic has been influenced by subsidence. The main part of Jutland from the Limfjord towards the south is covered by Miocene deposits, which built out towards the depocentre in the central part of the North Sea. Four main sequence boundaries are recognised in the Miocene reflecting the lithological shift from fluvial sandstones to marine clays in the succession.

Pre-Quaternary geology of the Jammerbugt area

A large part of the area between the Jammerbugt and the Limfjorden is geomorphologically a very flat lowlying terrain, which reveal no evidences of strong tectonic activities. In the subsurface, however, complex dynamic activities are concealed. This can be illustrated by comparison of the two subsurface geological maps of the Jammerbugt area Figs 4 and 5. The important structural feature governing the geological development is the Fjerritslev Fault, which was active from early Triassic (250–200 mill. years ago) and resulted in considerable subsidence. An up to 6 km thick succession of Triassic sandstone and conglomerates was accumulated, and the subsidence continued during the Jurassic and the early Cretaceous, when clay stone and greensand were deposited with a thickness of up to 2,5 km (Fig. 4). For comparison it is seen that at the end of the Cretaceous the picture has been inverted. Now the former subsidence area has become an area of uplift. The subsidence, on the other hand, has moved to the area on the west side of the fault zone to the depression between Bulbjerg and Hanstholm (Fig. 5). An even clearer picture of the thick successions in the Fjerritslev Trough is seen in the N–S trending cross-section through Denmark in Fig. 6.

Figure 3. *The Stevns Klint cliff section with the choir of Højrup Church situated on the top of the formerly rock-fall affected cliff section. The lower part of the cliff consists of uppermost Maastrichtian chalk, while the upper part of the cliff is build up by bryozoan mounds to form the Danian limestone. The Fish Clay at the Cretaceous/Tertiary boundary forms the top of the lower part of the cliff, which suffers strong erosion. The orange-brown 2-3 m thick layer on top of the cliff is clayey till deposited by the Baltic Ice advance about 17 000 BP.*

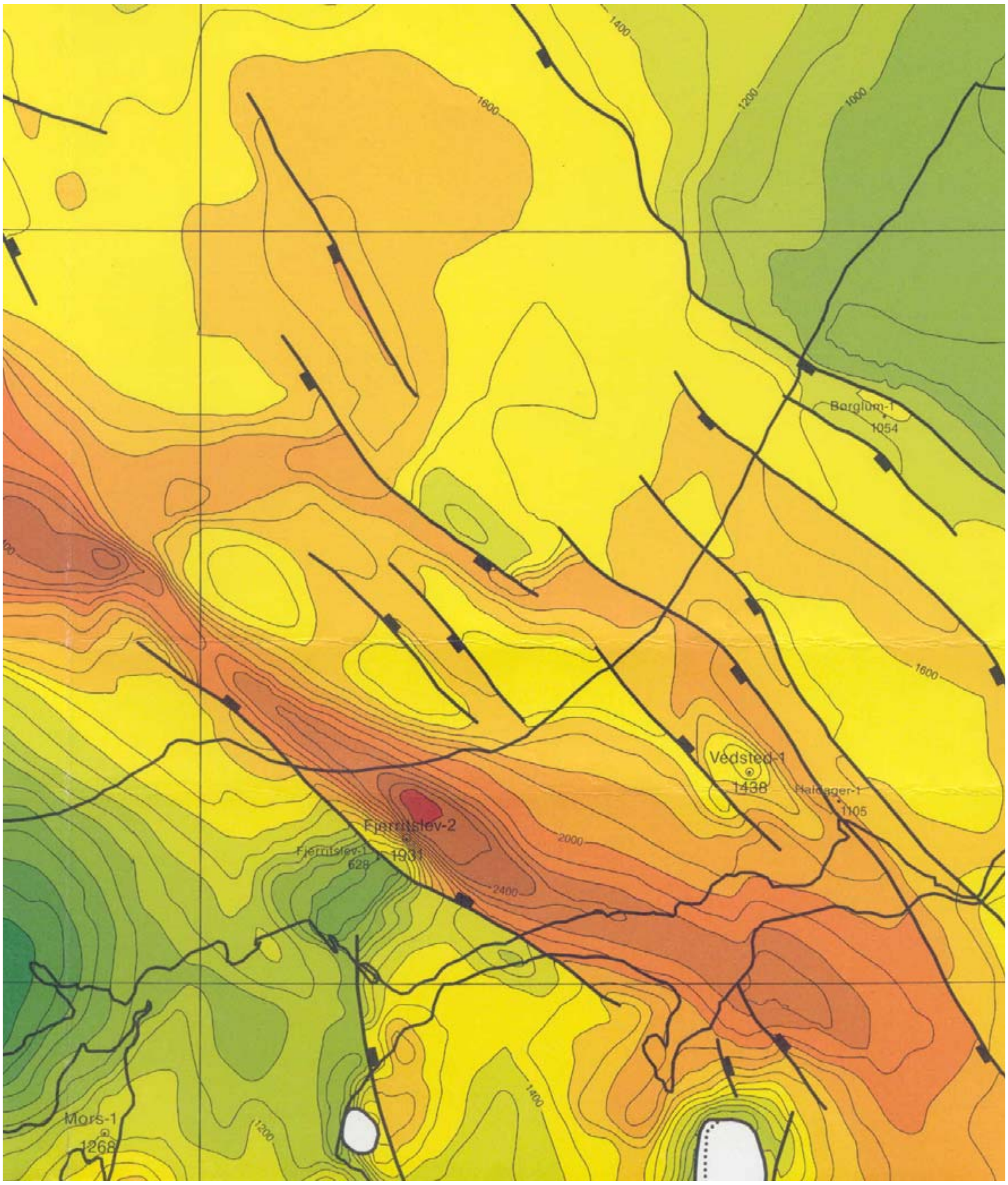

Figure 4. *Isopach map showing the thickness of the Jurassic and Lower Cretaceous deposits in the vicinity of the Fjerritslev fault structure. The contours on the map are 100 m, and consequently the deposits in the depression north of Fjerritslev contain a more than 2.5 km thick succession of Jurassic-Lower Cretaceous sediments. South-west of the fault the same succession is only 600–800 m thick. This uplift is interpreted as due to a salt-structure similar to the salt-structures indicated by white areas further to the south. After Japsen & Langfofte (1994).*

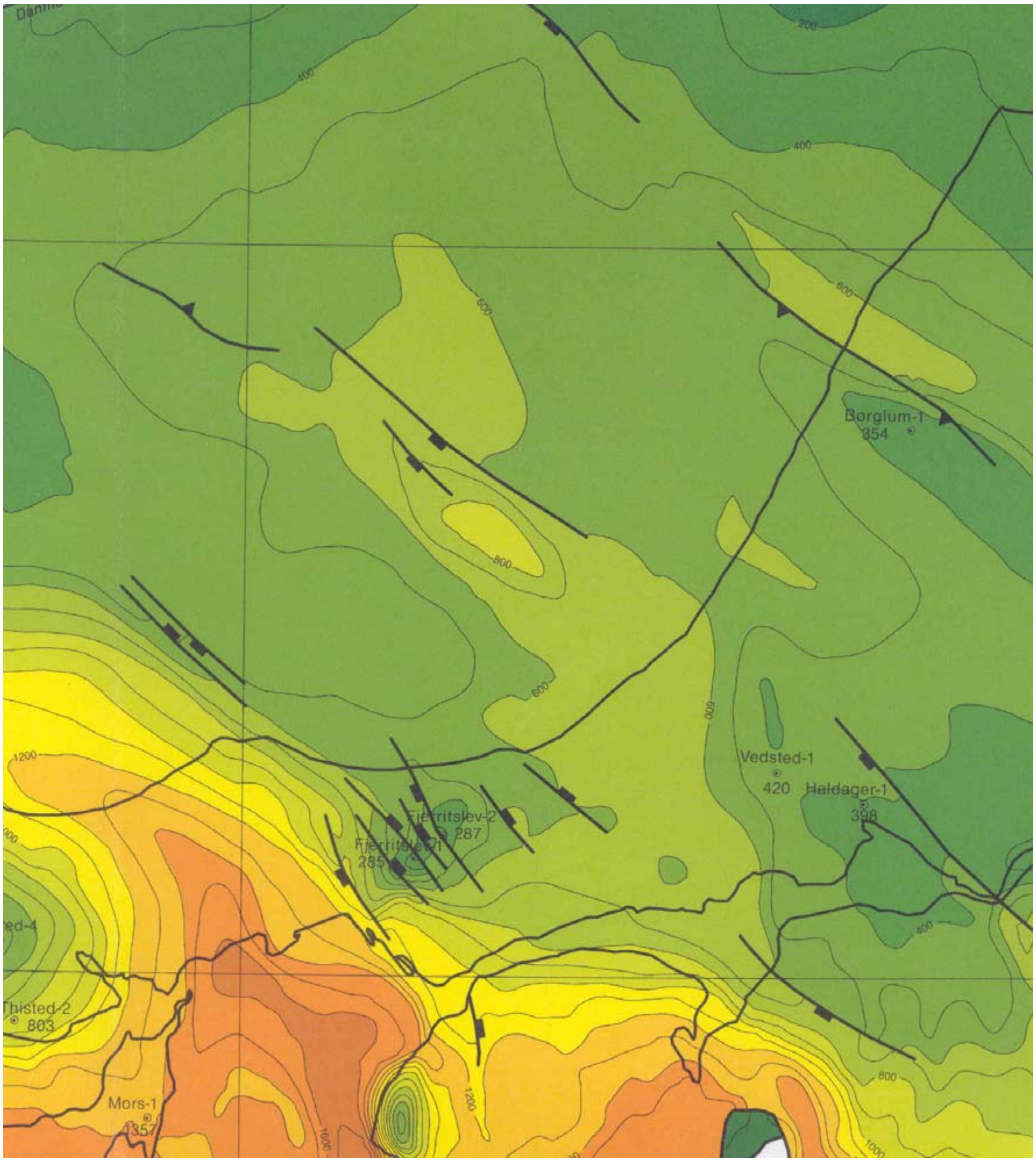

Figure 5. *Isopach map showing the thickness of the Chalk Group. The main part of the Chalk Group comprises chalk and pelagic carbonate from the Upper Cretaceous as well as the Danian limestone. After Japsen & Langtofte (1991).*

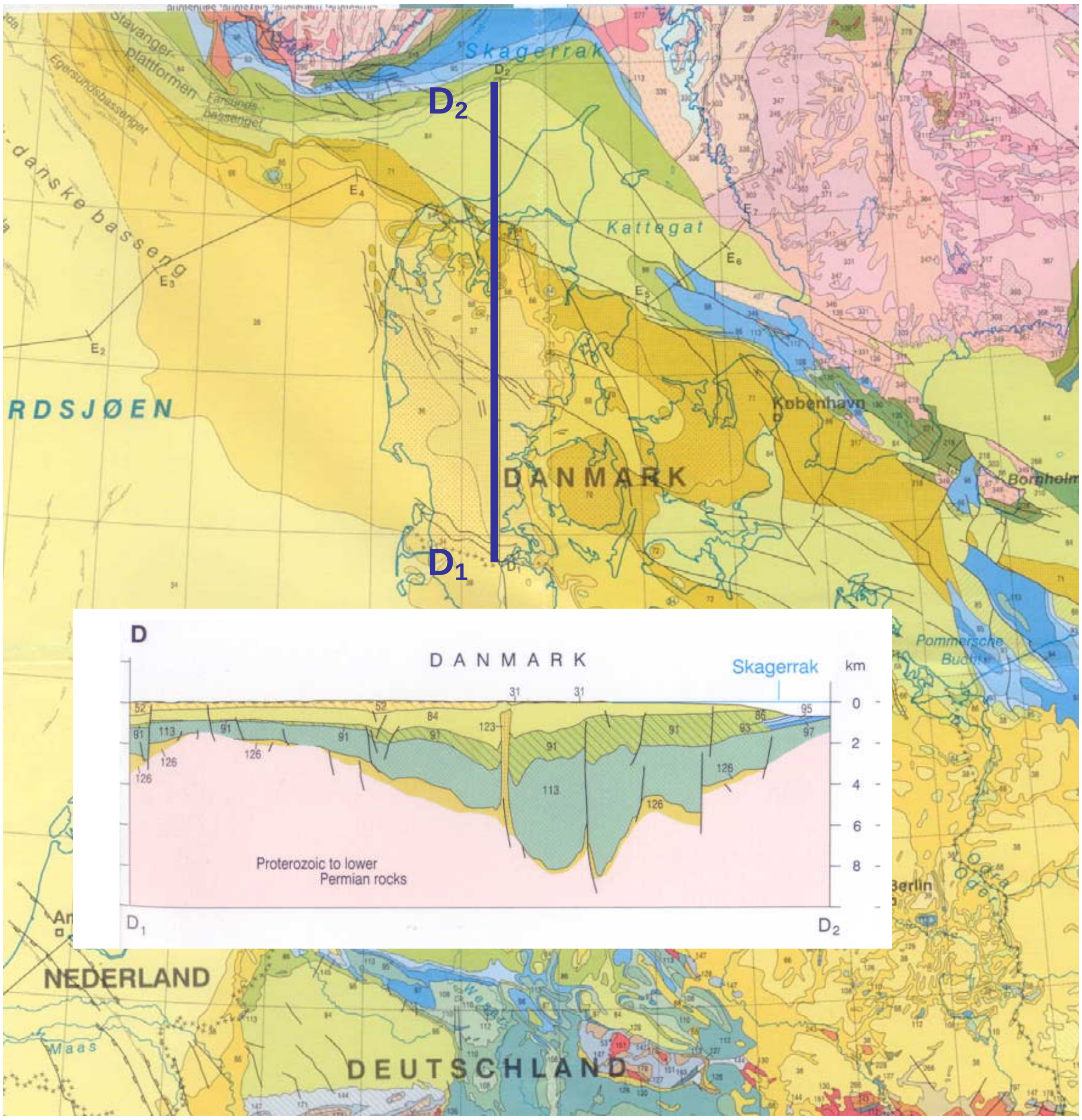

Figure 6. *Geological map of the Danish Basin with a N–S directed cross-section (D_1–D_2). In the cross-section the light red color marks the basement below Denmark, which consists of gneisses and granites. Note the Ringkøbing-Fyn High in the southern part of the cross-section. The thick green unit (113) is the Triassic deposits. The green hatched area above are Jurassic and Lower Cretaceous deposits, whereas the light green unit (84) is the Chalk Group. The salt diapir (123) is the Tostrup structure in the south-western part of Himmerland. Note that the cross-section is extended by 1½ in relation to the length of the location line on the map. From S.A.S. Pedersen, P. Gravesen & O.V. Vejbæk's contribution to Sigmond (2002).*

Topography of the Chalk Group surface

The large tectonic displacements in the subsurface are directly mirrored in the distribution of the chalk below the Quaternary deposits (Fig. 7). It is seen that the chalk surface is elevated at Svinkløv and in the hills south of this fossil coastal cliff. Furthermore the chalk surface is at a relatively high level at Bulbjerg and Klim Bjerg, both of which formed fossil islands during the postglacial, when eustatic sea-level was high and glacioisostatic rise was not yet complete. However, from Bulbjerg and Klim Bjerg the top surface of the chalk slopes westwards to more than 100 m below sea level. Further to the west, at Hanstholm, the chalk is elevated again and is seen in various outcrops (Fig. 8).

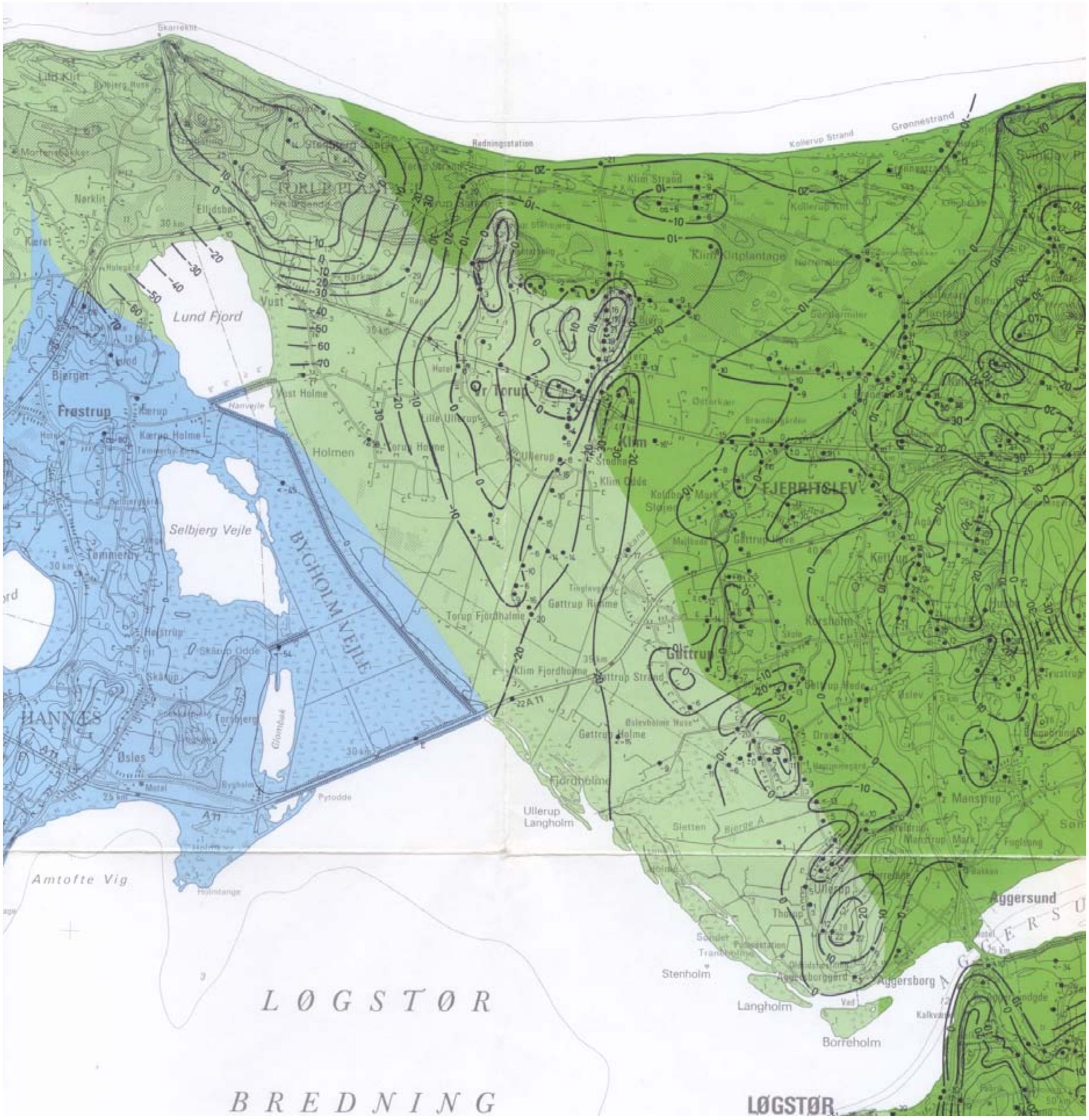

Figure 7. *Map of the topography of the upper surface of the Chalk Group. The distance between the contour lines is 10 m. Note the high elevation of the chalk towards Fjerritslev. Green is Cretaceous chalk, light green I Danian limestone. Blue color is Eocene diatomite with ash layers. From Gry (1979).*

The Hanstholm salt dome, also called the Thisted Structure (Fig. 8), is a flat salt pillow that raises the Chalk Group up into a huge shield shaped high. The flanks of the structure are outlined by the Danian limestone, which form marked chalk ridges in the landscape, instructively outlining the salt structure in the subsurface. The top of the salt is situated about 3,5 km below the surface.

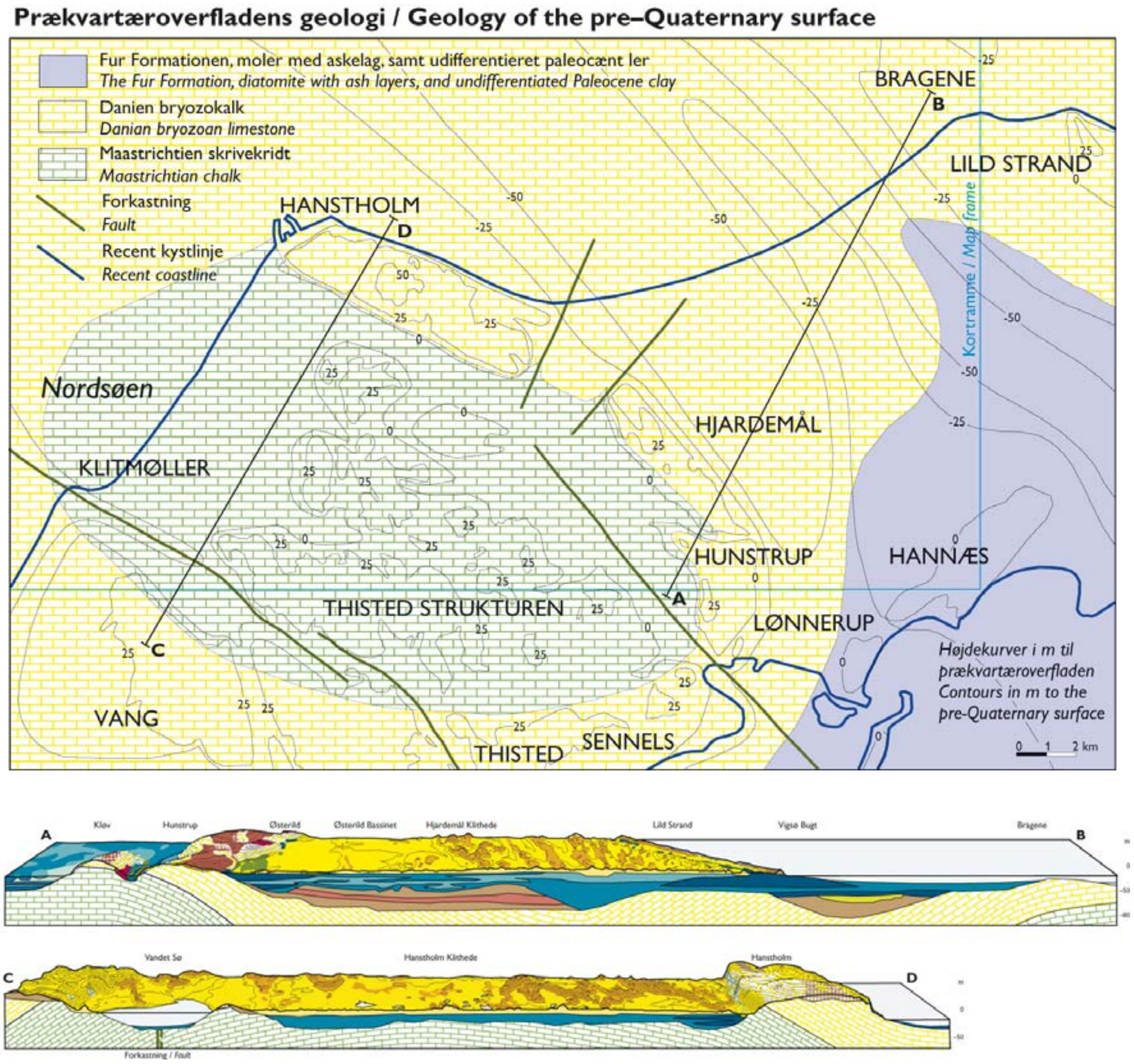

Figure 8. *Geological map of the bedrock above the Hanstholm salt dome (Thisted Structure) and two cross-sections illustrating the geological framework on the northern flank (A–B) and the doming in the central part of the structure (C-D), respectively. Note the WNW-trending fault zone at Klitmøller. Recently a groundwater well has here been so popular that people in Klitmøller bottle and distribute mineral water from this locality. The yellow unit of top of the cross-sections indicates aeolian sand with the highest dunes outlined in orange. The blue colour below the dune areas represent marine deposits from the postglacial Atlantic time. (From Pedersen & Petersen 2002).*

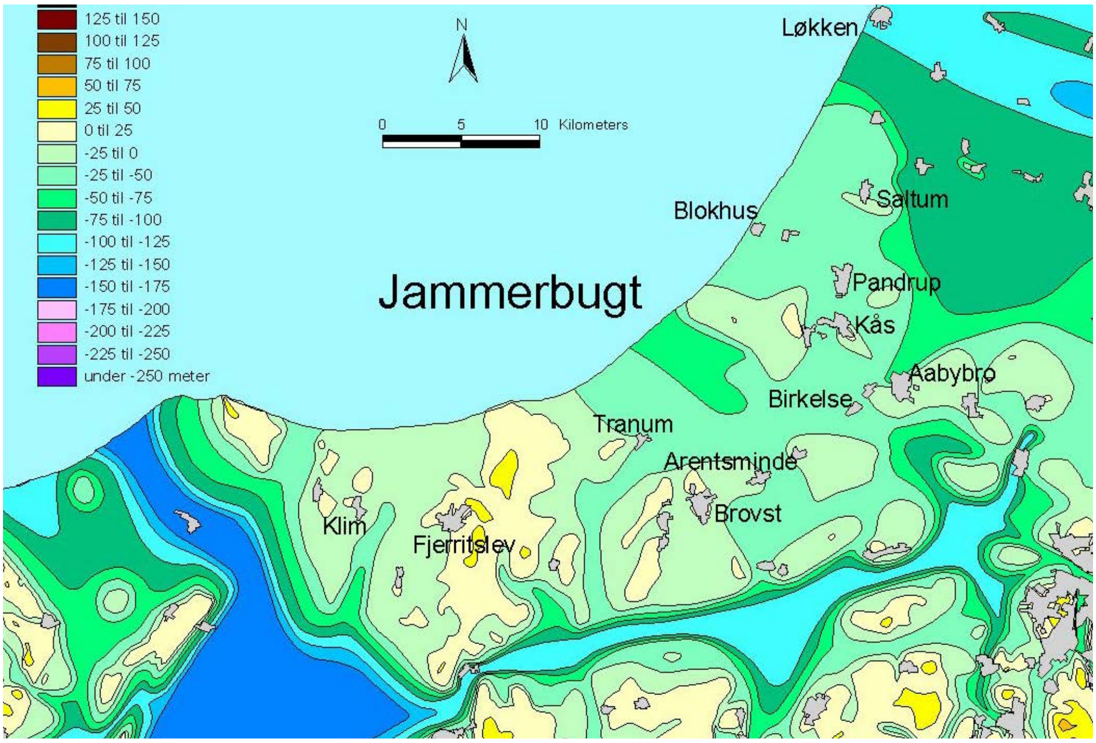

Figure 9. *Topography of the Pre-Quaternary surface in the Jammerbugt area. The map is based on the groundwater well data base at GEUS. Compare the map with the map of the terrain topography for the same area Fig. 10.*

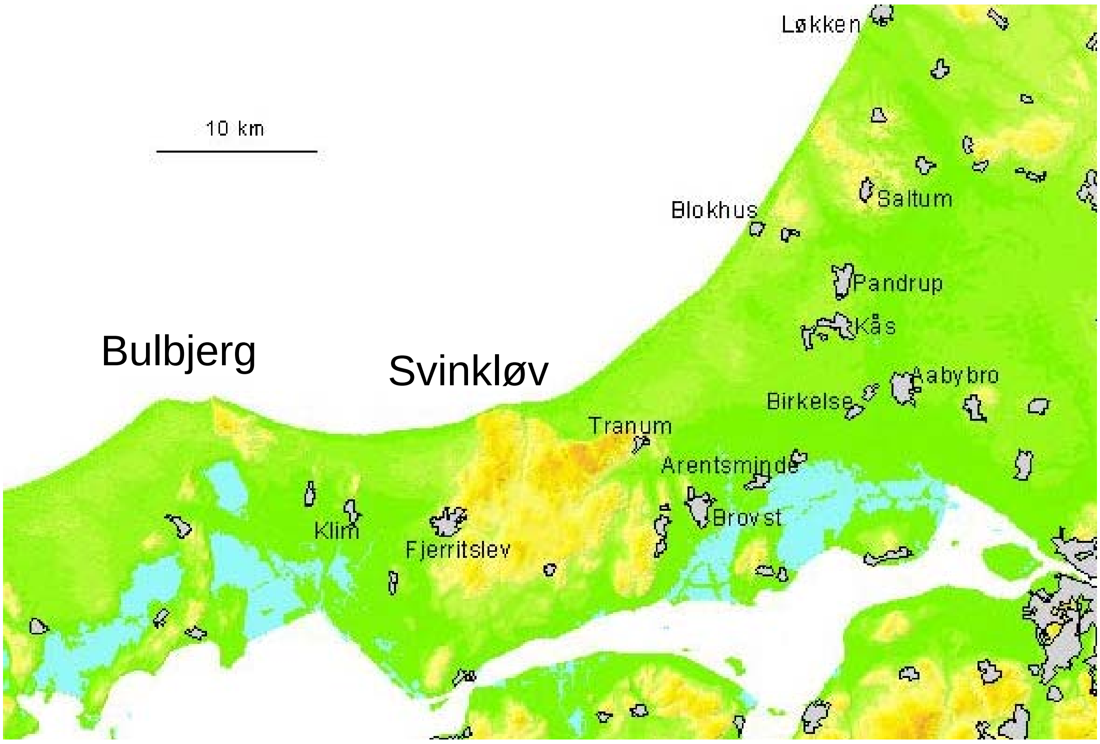

Figure 10. *The map of the present topography is here outlined in a digital terrain model. The darkest yellow colors are hills about 55 m above sea level, and blue indicates dammed areas at sea level. The map is based on Top10DK.*

Quaternary geology of the Jammerbugt area

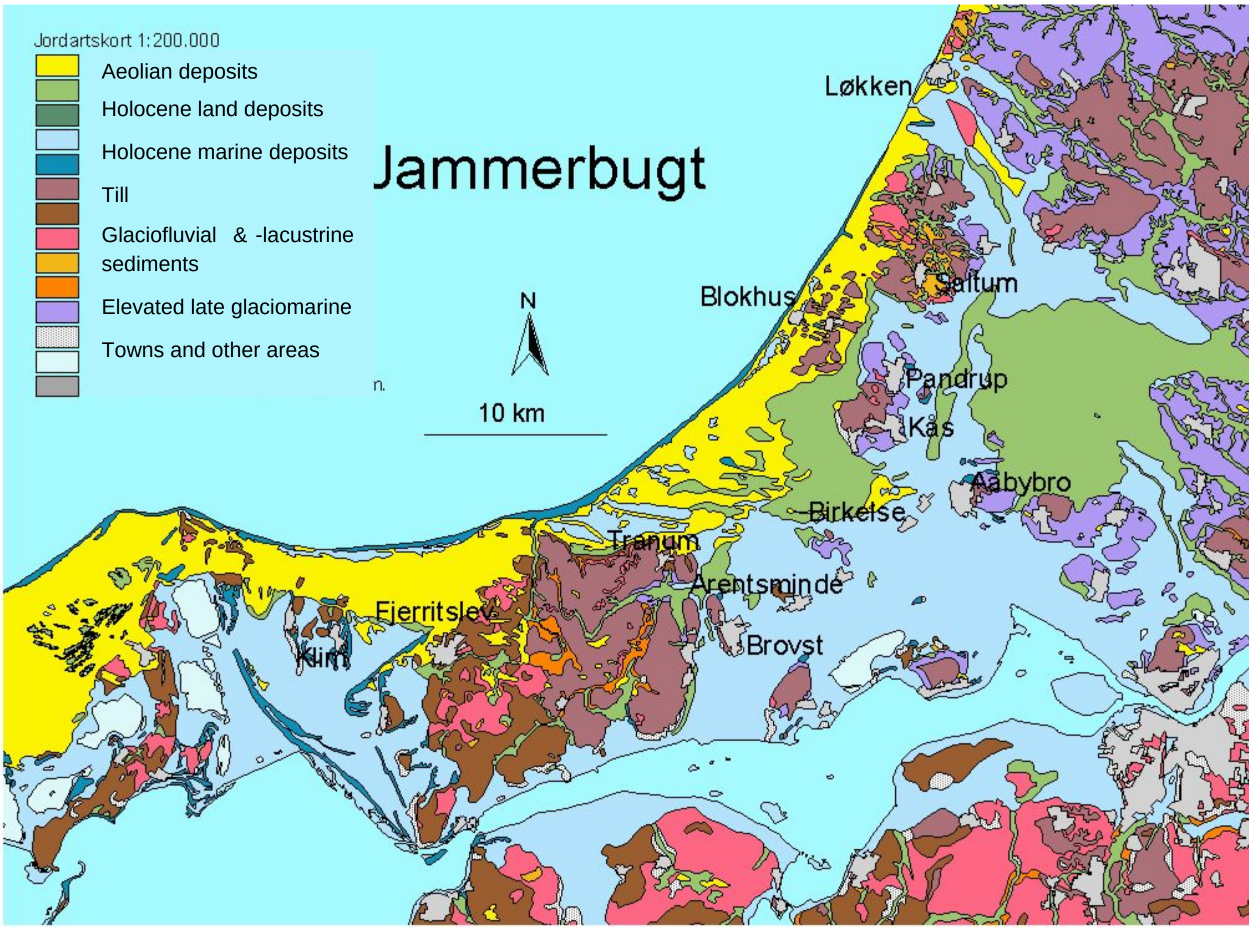

Figure 11. *The map of Quaternary deposits in the Jammerbugt area. After Pedersen (1989).*

The Quaternary deposits are divided into three groups: 1) The glacial deposits, 2) the late glacial deposits, and 3) the post glacial deposits. The glacial deposits comprise glaciofluvial sand (indicated with red color on the map Fig. 11), clayey till and sandy till (brown color in Fig. 11), and the extra-marginal deposits of clay and sand (orange color in fig. 11), which were deposited in the dead-ice dominated landscape during the melting back of the Scandinavian Ice Cap. The glacial deposits were mainly deposited during the advances of the ice from Norway and Sweden between 30 000 and 20 000 years BP.

The late glacial deposits comprise fine-grained, laminated sand and clay, which was deposited in the arctic sea that covered the Jammerbugt area and areas further to the north after the Scandinavian Icecap melted back from northern Jutland. These marine deposits were formerly referred to as the Yoldia clay and Saxicava sand (after two characteristic bivalves) (Fig. 13), but they are now part of the recently established Vendsyssel Formation. The formation is dated to 17 000 – 14 000 years BP, and the alternation between clay and sand is interpreted to reflect the variations in water depth caused by interplay between glacio-isostatic uplift and eustatic sea level rise.

The post glacial deposits are shallow marine beds and freshwater peat dominantly occupying the St. Vildmose bog north of Åbybro and BIrkelse. The youngest sediments are the aeolian dunes that migrated landwards from the coastal areas, mainly 200–300 years ago.

The glacio-isostatic elevation

Figure 12. *Map of isobase contour lines in northern Denmark. The blue lines show the present day altitude of shoreline formed during the Atlantic transgression about 7 500 years BP. The red lines show the present day altitude of the shoreline formed during the late glacial transgression, which led to deposition of the Vendsyssel Formation. From Mertz (1925).*

During the glaciation the continental crust was depressed by the weight of the icecap. When the ice melted away an isostatic rebound began and the equilibration is still sontinuing. In the central part of northern Scandinavia this rebound is up to 800 m, but the maximum rebound in Denmark is recognised at Frederikshavn to be about 60 m. In Fig. 12 the successive decrease in elevation is demonstrated by the contour lines, which indicate a consequent direction of decrease towards the SW. At Ringkøbing Fjord the isostatic elevation is regarded to have ceased, and south of the Ringkøbing-Fyn High a general subsidence affects the landscape.

It was the geologist and geotechnical expert Ellen Louise Mertz who collected and published the data that made it possible to reconstruct the uplift, today referred to as the glacio-isostatic rebound. Many of the data that Mertz based her mapping on are not available any more, but the significant fossil coastal cliffs are still easily recognized in the landscape along the Limfjorden and in the Jammerbugt area. The elements upon which Mertz based the elevation data are: accumulation terraces, erosion terraces, beach ridges, accumulations of sea weed, coastal cliffs and coast lines, boundaries of marine deposits, marine shell gravel, shell beds in peat and eve deposits.

The evidence of isostatic elevation was fairly well understood already in 1920. However, the Atlantic transgression was neither well established nor understood. Since then the understanding of the global sea level rise has increased, and today it is so well supported that we believe the total eustatic sea level rise is about 120 m since the last glacial maximum. The first part of this rise may well be the melting down of the Scandinavian Icecap as well as large ice caps in Siberia. This event was probably outpaced by the rapid isostatic rebound that changed northern Jutland from sea floor to land where reindeers roamed on a huge steppe, which extended far out into the present day North Sea and Kattegat. During the Stone Age the sea level rose about 30 m over 500 years (the Littorina transgression), mainly caused by the melting down of the North America Icecap. Subsequently the last isostatic rebound in northern Jutland started about 7 500 years ago, and at Løkken in the northern part of the Jammerbugt area it reaches 9 m above recent sea level (Fig. 14). For comparison the elevation of the same seafloor further south is about 5 m below the peat in the St. Vildmose bog.

The St. Vildmose peat-bog is an interesting example of the environmental disaster that affected the Ion Age people. After the isostatic uplift had drained the seafloor of the Stone Age Sea the flat land area developed into a wet bog and heather. Around the birth of Christ the bog expanded, and 700 years later all of the heather was covered by bog peat. Remains of the last Ion Age people have been dated to 300 years AD, when they secured safe passage across the bog by arranging boulders along the tracks through the bog. However, their efforts were not sufficient to cope with the dramatically expanding peat and they had to give up living in this environment.

Figure 13. *The thin clay and sand layers in the Vendsyssel Formation. Note the burrows in the sand and the shells preserved in live position. The shells are the arctic marine bivalve Hiatella arctica formerly known as Saxicava. The beds in the picture are elevated 25 m above sea level.*

Figure 14. *The coastal cliff head Løkkens Blånæse. The blu-grey beds in the lower part of the cliff are marine peat and gyttja-rich sediments deposited in a fiord during the Atlantic time. Since then the marine deposits have been elevated 9 m above present sea level. The cliff is capped by yellowish aeolian dune sand.*

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