DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/11

Glacial deposits, glacigene lithofacies and glacigeological environments – examples from the Late Pleistocene settings in Denmark

Excursion guide to geological key localities of glacial deposits in north-western Denmark to be compared with palaeo-glacial deposits of Ordovician age in nothern Africa

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MINISTRY OF CLIMATE AND ENERGY

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Relative denudation chronology in NE Brazil based on mapping of large-scale landforms

Contribution to the project "Burial and exhumation history of NE Brazil focussing on the Camamu Basin: a multidisciplinary study based on thermal, sonic and stratigraphic data and landform analysis"

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Glacial deposits, glacigene lithofacies and glacigeological environments – examples from the Late Pleistocene settings in Denmark

Excursion guide to geological key localities of glacial deposits in northwestern Denmark to be compared with palaeo-glacial deposits of Ordovician age in northern Africa

Provided for StatoilHydro March 2009

by

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Introduction

Glacial geological settings are primary known from the most recent part of the geological history due to the fact that we have just passed the last ice age and are living in the middle of an interglacial period. The remnants of the last glacial period are well preserved, and in the cold, remote areas of the globe recent glacial processes are still acting. However, glaciations are not restricted to our own geological period, the Quaternary, but due to cosmic conditions and plate tectonic constellations glaciations also affected various parts of the continents repeatedly throughout the geological history. The earliest glaciation is of Proterozoic age, which has been recorded from Norway (Varangrian glaciation), Greenland, Scotland and America and has contributed to the hypothesis of a snowball earth. In the Lower Palaeozoic glaciations are typically related to the plate-tectonic setting illustrated by the distribution of various climate zones in the Ordovician: At the same time glaciation appeared in northern Africa, Peary Land in north Greenland was located in a setting, where a carbonate platform built up similar to the Great Barrier Reef. The conclusive interpretation is that while north Greenland in the Ordovician was located close to Equator, northern Africa had its position close to an arctic pole, namely the South Pole, whereas today we have the opposite situation. Other records of glaciations are known from Australia, which was part of Gondwana Land in the Permian.

For the comparison of young glacial deposits with ancient glacial sedimentary rocks Denmark provide a large number of excellent exposures in coastal cliffs and raw material pits, where glacial successions can be studied. Furthermore, examples of glacial environments are easily demonstrated and the main part of the landscape is created by glacial geomorphologic elements. This report aims at representing the basic concepts of glacial geology exemplified by selected localities in western and north-western part of Denmark, to be demonstrated in a field course for participants from StatoilHydro in March 2009.

The glacial sequence system

Due to the increasing number of proxy data on temperature variations during the Quaternary it is now generally accepted that the Milankovitch cycles are of crucial importance for the development of cold and warm climate on the Earth. Thus the first half part of the Quaternary was dominated by the temperature variations caused by the 41.000 years cycles related to the variation in the tilt of the Earth's rotation axis, which resulted in a more frequent shift between glacial and interglacial events. From about 800.000 years ago the 100.000 years cycle related to the eccentricity of the Earth's orbit around the Sun took over resulting in longer glacial/interglacial events. These periods are well recorded in depositional settings in North Europe, where the periods are known as Cromer (interglacial), Elster (glacial), Holsteinian (interglacial), Saalian (glacial), Eemian (interglacial), and Weichselian as the last glaciation (Fig. 1).

The Holocene time can be regarded as the last interglacial event, which started 11.300 years ago (Lowe & Walker 1997). It might be argued that since we have not experienced the preceding glaciation, the Holocene can only be regarded as the end of the glaciation. However, the cyclicity of the temperature curves and its agreement with the Milankovitch cycles makes it reasonable to believe that a new ice age may start in some thousand years. The last interglacial period, the Eemian, lasted 15.000 years, so we may be more than half way through the present interglacial period. Comparison between the transition from the Saalian to the Eemian and the shift from the Weichselian to the Holocene is markedly different. Therefore one has to expect some differences in interglacial duration depending on the interference of the short Milankovitch cycles, the wobble of the Earth's rotation axis, on the longer ones.

Related to the glaciations some of the most dramatic changes in the depositional systems occurred. This is partly due to the enormous amount of material moved around by the ice streams, and partly due to the dramatic shift in eustatic sea level (Figs 2 & 3). Moreover, the discharge of water from the ice caps during melting contributed to depositional systems in the terrestrial environments.

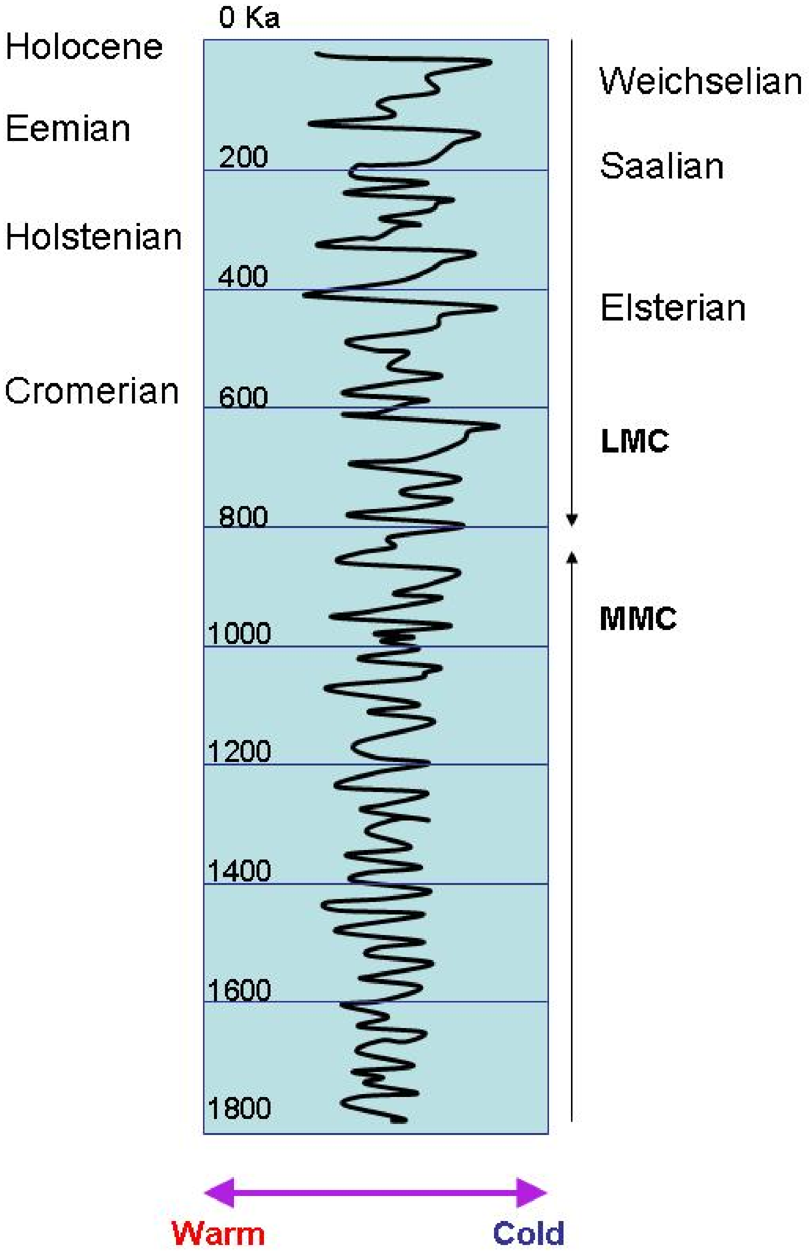

Figure 1. *Temperature changes through the main part of the Quaternary from 1.8 million years before present until to day. The curve is based on* O^{18}/O^{16} *ratios measured in the calcite of foraminifers deposited in deep-sea sediments. The warm climate periods are indicated by the peaks in the left side of the diagram, and the cold climate with glaciations to the right. The shift from relatively shorter Milankovitch cycles (MMC) to dominance of the longer periods (LMC) is indicated to be situated about 800.000 years ago. The naming of the glacial–interglacial times are given for the last third of the Quaternary. The climate curve is based on Lisiecki & Raymo (2005).*

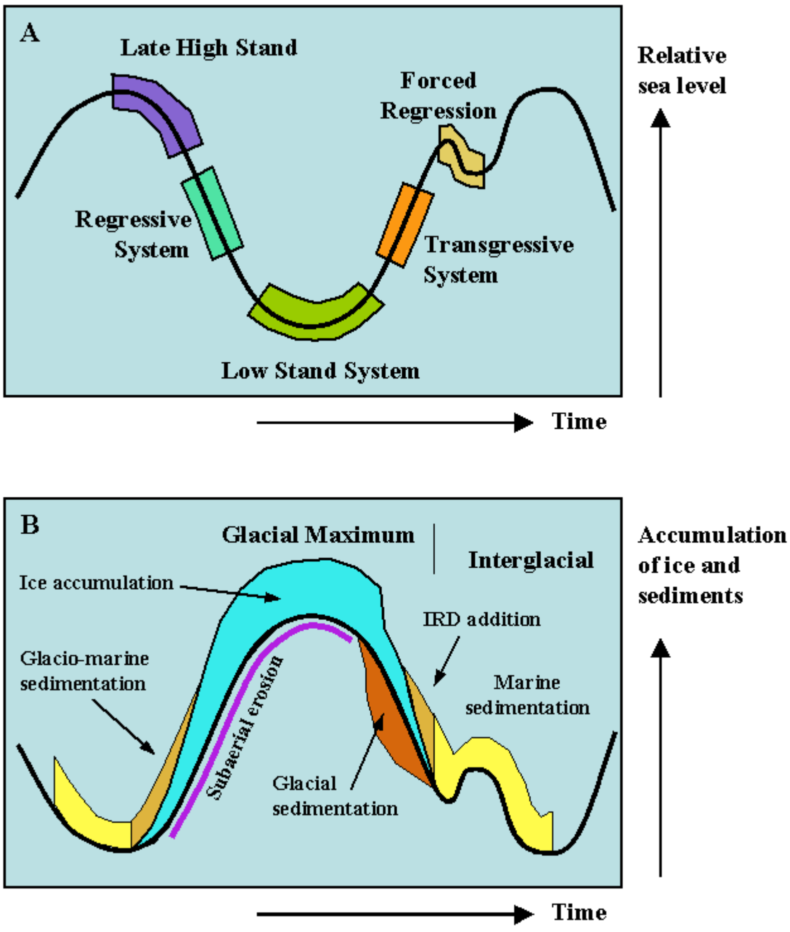

Figure 2. *Two diagrams showing the relation between high-stand–low-stand systems. A) Illustrates the general sea level curve from the maximum sea level stand to the lowest sea levell and back again. Note the forced regression on the transgressive part of the curve which is caused by glacio-isostasy. B) Illustrates the mirrored curve with depositional environmenst. Note the occurrence of ice rafted debris (IRD) in the sediments deposited during the maximum discharge of ice from the ice caps during the main transgression.*

The high-stand – low-stand system

The most obvious consequence of a glaciation is a eustatic fall in sea level. During the accumulation of ice, the sea level will fall, which in the last glaciation resulted in a 120 m lower sea level compared to the present. This was mainly caused by accumulation of ice in the Antarctic, Greenland and North America, Siberia, Scandinavia and the mountain ranges in general.

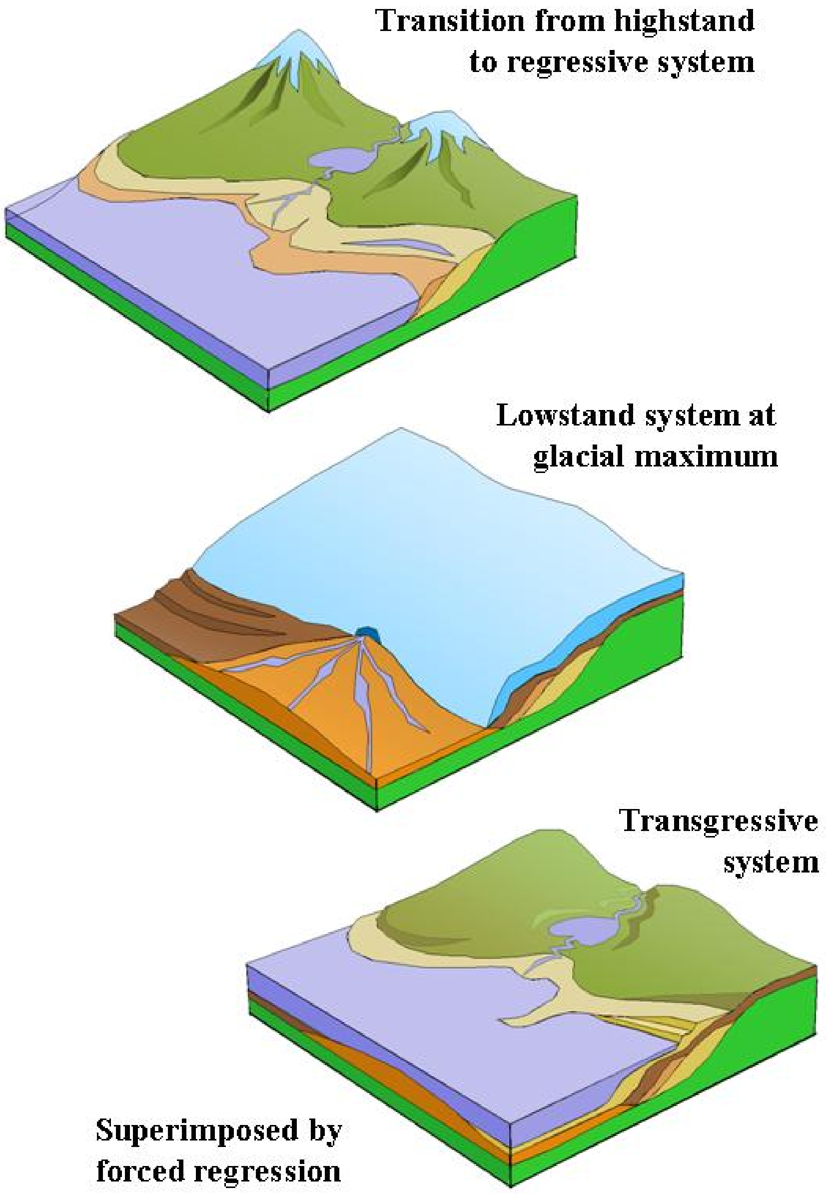

Figure 3. *The development of glacial influenced environment during the evolution from high-stand via lowstand system to transgressive system. The latter is illustrated with the influence of forced regression due to glacio-isostatic rebound.*

At the beginning of a glaciation the sea in the polar-near regions turns into an arctic marine environments, and subsequent the high-stand system turns into a regressive system during the initial accumulation of ice (Figs 2 & 3). During the regression shallow marine deposits prograde towards the deeper parts of the basin, and glacio-marine faunas invade the environment. In the terrestrial environment the sediment accumulation is sparse, but a number of arctic or sub-arctic lakes form in the increased space of the lowland areas. The preservation potential of these deposits may be questioned, because subsequent glacial erosion and erosion during transgression could easily remove the sediments.

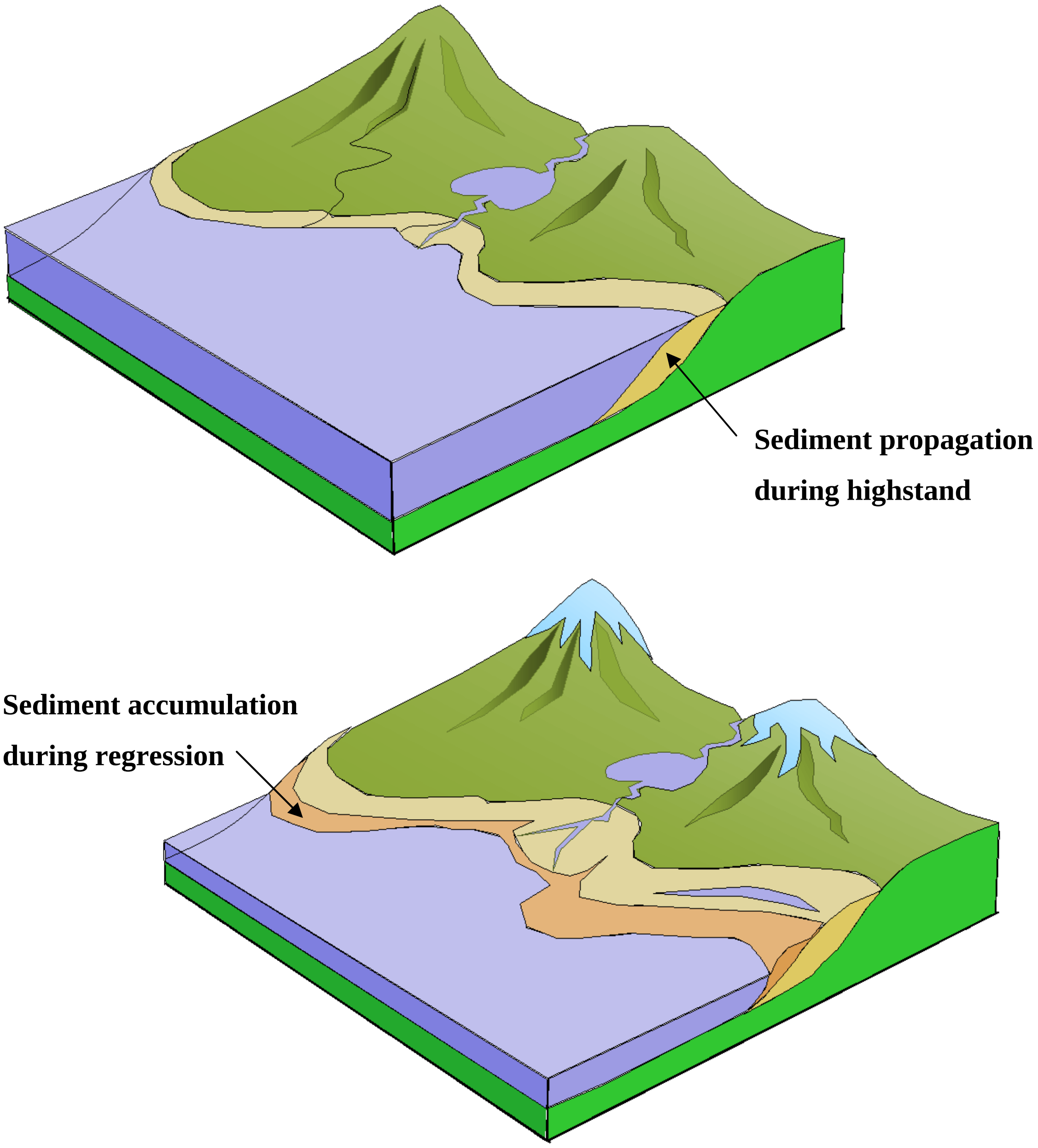

Figure 4. *Block diagrams illustrating the transition form late highstand to regressive system.*

When the peak of the maximum glaciation is reached, the low-stand system prevails. In the terrestrial environment subaerial erosion increases, and on the permafrozen plains aeolian deposits migrate over the sparsely vegetated environment. Due to gravity spreading the ice caps advance from the accumulation areas towards the lowland. Shortly after the maximum glaciation the translation of the ice sheets increases, and the discharge from the ice results in the deposition of melt-water sand and gravel in the outwash plains (glaciofluvial deposits in the sandur). The glaciofluvial deposits prograde progressively in the proglacial environment in front of the ice margins, and as a result thick sheets of coarsening upwards sand and gravel covers the terrestrial lowland plains. However, it is not only the glaciofluvial deposits that characterise this environment. At the base of the ice a lodgement till will be deposited, thus the top of the glaciofluvial successions is overlain by a till resulting from the transgression of the ice sheet.

The shift from cold to warmer climate and the consequently melting back of the ice caps, results in a transgression system due to the eustatic sea level rise. Glaciomarine muddy sediments are wide spread outside the coastal environment, and the marine deposits are characterised by the abundance of ice rafted debris (IRD) typically deposited as dropstones from the frequent appearance of icebergs in the sea (Fig. 2). However, the transgression system is disturbed by a forced regression caused by the glacio-isostatic uplift of the former depressed landmasses. In this way a shift from a former shelf mud deposit into a shallow marine succession may even be exposed on shore (Fig. 3).

The highstand – lowstand transition, from interglacial to glacial conditions

The last interglacial time, the Eemian, ended about 115.000 years ago. The terrestrial conditions changed from woodland into a tundra steppe inhabited by reindeers and mammoths. In Denmark the change was recorded from the lake Solsø located in the Saalian landscape, which was not glaciated during the Weichselian (Jensen & Milthers 1928). The marine conditions are recorded in the 235 m deep the Skærumhede well in northernmost Jutland (Jessen et al. 1910), where the unconformity to the Cretaceous bedrock is located in 200 m's depth. Above this pre-Quaternary surface 20 m of Saalian glacial sediments are overlain by 33 m of marine Eemian deposits, which grade into a ca. 80 m thick succession of marine mud with a shelly fauna indicating increasing arctic-marine conditions culminating with the arrival of the bivalve *Portlandia arctica*. Just before the glacial maximum in the Weichselian, the marine conditions in the northern part of the Danish Basin changed into brackish and glaciolacustrine environment preceding the advance of the Norwegian Ice Stream about 30.000 years ago (Jessen 1931, Sadolin et al. 1997, Pedersen 2005).

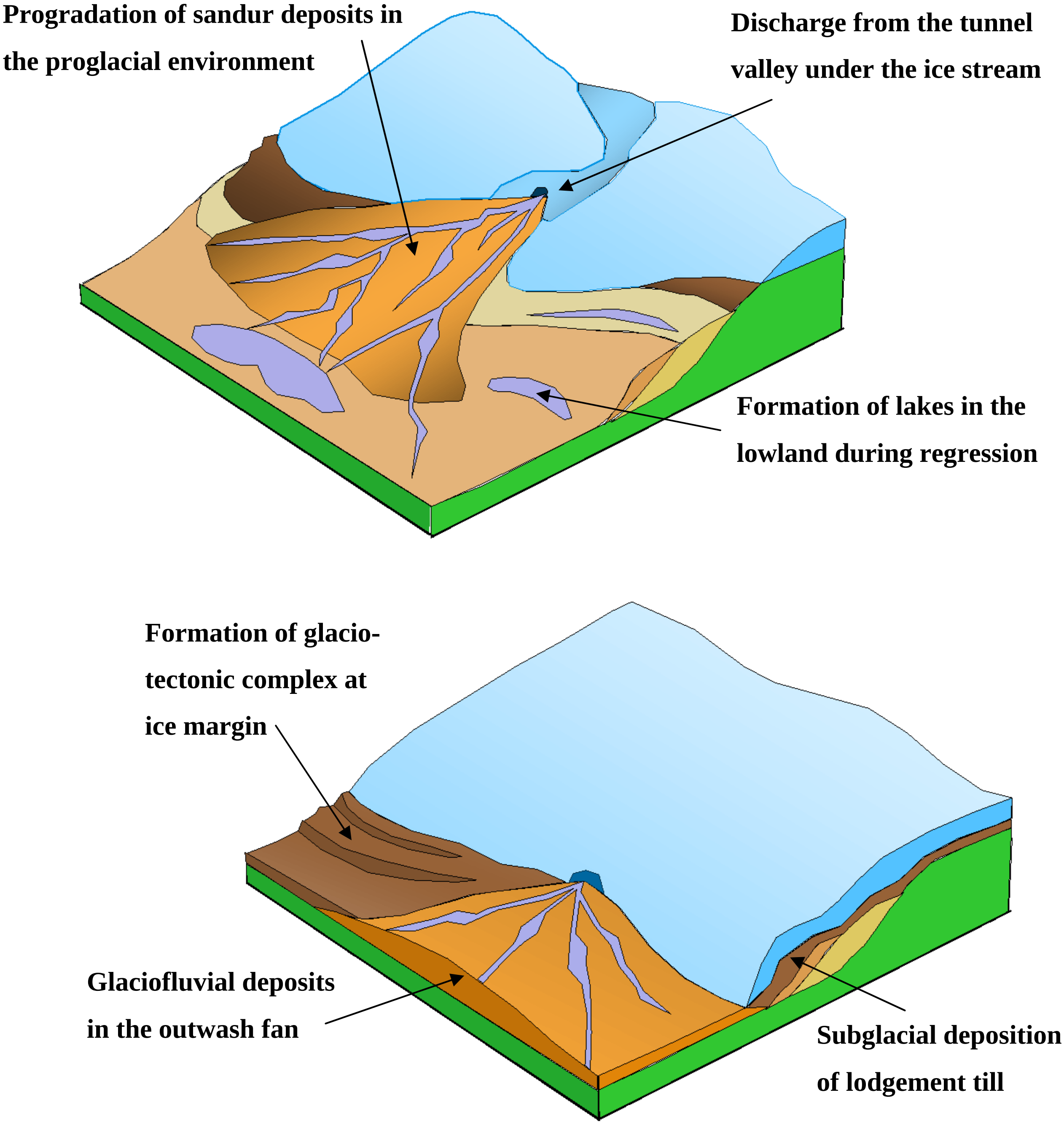

Figure 5. *Block diagrams illustrating the ice advance and the deposition of the sandur plain and formation of a glaciotectonic complex at the glacial maximum.*

The termination of the lowstand system and the development at the glacial maximum

The thick succession of glacio-marine sediments in the northern part of the Danish Basin is probably partly caused by the glacio-isostatic depression at the margin of the Scandinavian Ice Cap. But at the glacial maximum 30–25.000 years ago the marine conditions were terminated and the British and Scandinavian Ice Caps covered the northern part of the North Sea Basin. In the southern part of the North Sea a mammoth steppe extended from the north European mainland to the British Islands enabling the mammoth to migrate to England. The maximum depth of this part of the North Sea is only 50 m and by the global eustatic sea level lowering of 120 m (Shackleton 1987) marine conditions would not have prevailed.

The greatest ice accumulation was at the beginning of the glacial maximum located in southern part of Norway from where the ice advanced towards the Danish Basin 30.000 years ago. The precipitation conditions along the Atlantic-Norwegian coastal region was probably the cause of this accumulation. The Norwegian Ice Stream was very rapid and could even have been regarded as a mega surge, and it was succeeded by a relatively fast melting of the ice margin leaving northern Denmark ice free for about two thousands years. At this time the ice divide in the Scandinavian Ice Cap migrated towards the east and a more steady ice advance arrived from the central part of Sweden towards the Danish Basin (Lundquist 1986, Houmark-Nielsen 2003, Pedersen 2005). The culmination of this ice advance was the creation of the Main Stationary Line (MSL), which outline the maximum extent of the Scandinavian Ice Cap. The MSL line can be followed from central part of Jutland to northern Germany and further to the east through northern Poland and to the northeast surrounding the Baltic States as well as Finland and Karelian up to the Barents Sea shelf. From the shelf off northern Norway and towards the south the MSL line is located offshore and runs via the North Sea into the coastal area of central Jutland, where a cross-section of the line can be studied at the locality Bovbjerg (Pedersen et al. 1988).

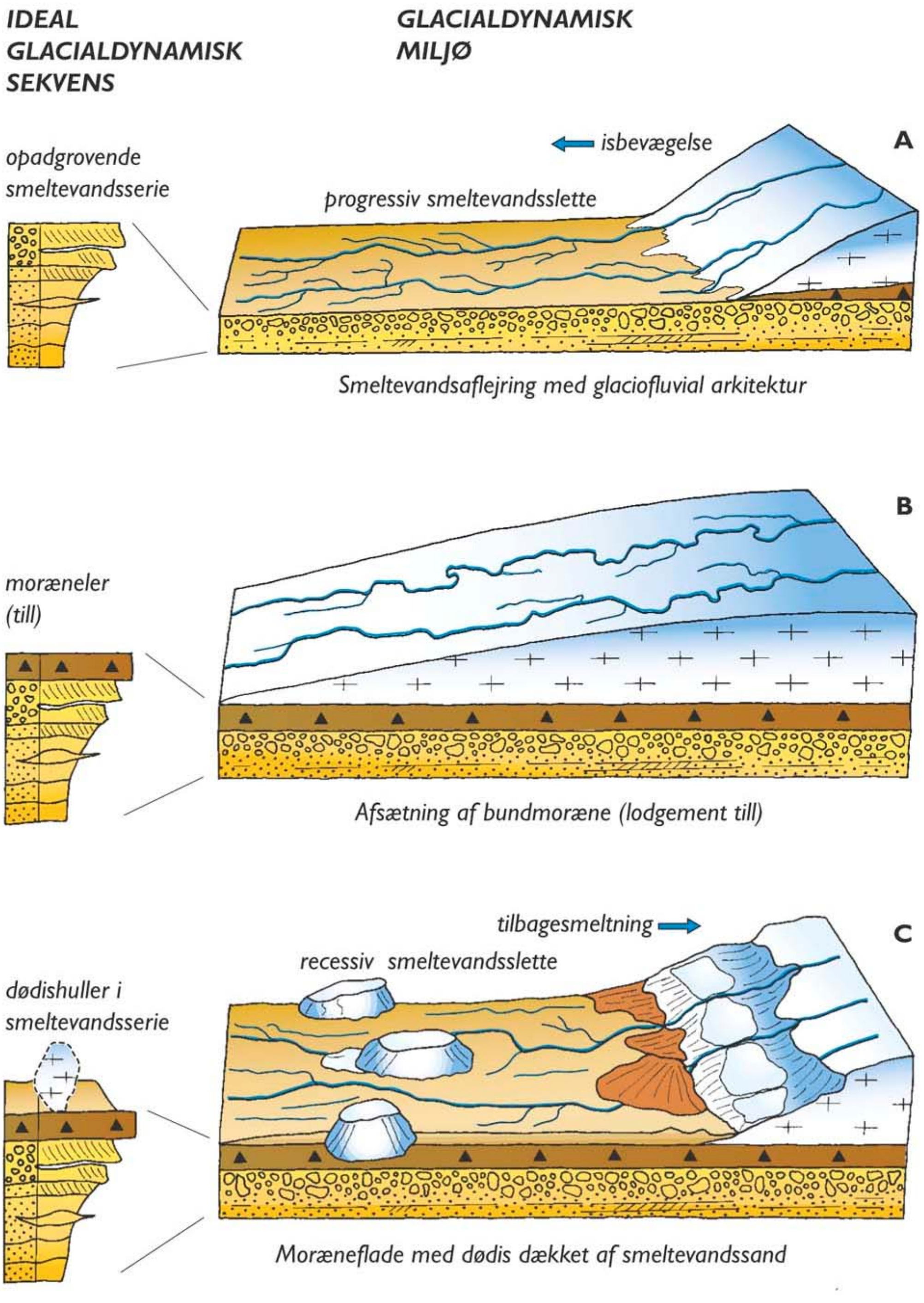

Figure 6. *Model of an ideal glaciodynamic sequence. A) Shows the early stage of the ice advance where a progressive sandur succession has been deposited in front of the ice margin. The log in the left side of the diagram illustrates the coarsening upward of the glaciofluvial sediments. B) Succeeding the deposition of the sandur unit the ice advances over the top and the lodgement till is deposited subglacially on to of the glaciofluvial beds. C) At the late stage of glacial development the ice melts back and block of dead ice are left on the moraine plateau. These blocks may be buried by the recessive glaciofluvial sediments. When a dead-ice block finally melts down, a characteristic kettlehole is formed in the otherwise rather flat landscape.*

The ice advance events have traditionally been based on the lithostratigraphy of the till deposits. In general these deposits vary in thickness from one to five metres and they are recognisable markerbeds for the stratigraphic correlation. However, the glaciofluvial deposits are by volume much more significant with a thickness three to five times the thickness of the till beds. The dominant glaciofluvial units are related to a proglacial setting with a prograding ice margin. The consequence of this depositional dynamic is a coarsening upwards sequence with fine-grained beds at the base and glaciofluvial gravel and even boulder beds at the top of the unit (Pedersen 1993). In the ideal sequence a till caps the unit. At the base of the till a glacitectonite represents the deformational layer below the ice stream and its lodgement till. This thin horizon, 0,1–1 m in thickness and formed by shear deformation, is also referred to as a glaciotectonic unconformity. The complete succession with glaciofluvial sediments overlain by a till, which due to dynamic features can be related to the same glacial advance are regarded as the lithological elements in a glaciodynamic sequence.

The glacitectonite is not the only type of deformation included in the glaciodynamic event. Proglacial glaciotectonic deformation of the glaciofluvial unit, as well as earlier sediments (Quaternary or older origin) is a characteristic part of the glaciodynamic sequence (Pedersen 1993, 2006) (Fig.). The deformation structures are described under the heading glaciotectonic complexes, the architecture of which can easily be compared to structures in mountain ranges, although smaller in scale still very impressive. The Danish Basin is well known for its abundance of glaciotectonic complexes of which Møns Klint is regarded as a classic type complex (Pedersen 2000, 2005). This complex as well as a dominant part of other complexes involves a pre-Quaternary sedimentary rock unit, which has been thrust up into an imbricate fan. During thrusting the propagation of ramps resulted in the formation of hanging-wall anticlines, and parallel ridges dominate the landscape after the ice has melted back.

The transgression system overprinted by forced regression caused by glacio-isostatic uplift

During the melting back of the ice the sea level rises dramatically. But in the tail of this an isostatic rebound follows and contributes by lifting the early deposited sediments of the transgressive system out of the sea. In the early phase of sedimentation during the raised sea level a fine-grained mud is deposited at the seabed. When the steadier isostatic uplift starts to influence the marine environment, shallow marine sediments are accumulated. In the lower part of the succession dropstones are found indicating the occasionally passage of icebergs. Even traces of iceberg deformation due to grounding icebergs can be recognised in the shallow marine deposits (Fig. 7). Typically for the shallow marine deposits are storm sand beds and trace fossils recording the inhabitation of a rich fauna in the well oxidised seawater rich in nutrients. In northern part of Denmark the seabed of the glaciomarine Yoldia Sea has been elevated up to about 50 m above present sea level. At Oslo the isostatic rebound is more than twice this amount.

Two marked features are related to the late stage of isostatic uplift, namely the preservation of former coast lines and the generation of spit systems (Fig. 8). The fossil coast lines can either form marked cliffs in the landscape or can be preserved as beach ridges forming concentric patterns inland from the beach. The spit systems are accumulations of material transported from areas of cliff erosion along the coast to areas of deposition. The spit system will be in a difficult equilibrium position where newly deposited material is lifted out of the sea until the sediment loading starts to overrule the decreased isostatic uplift. This is well illustrated in the Skagen spit system, probably the largest spit system in the world.

Figure 7. *Storm sand beds deformed by grounding of an ice berg. Middle part of the Vendsyssel Formation at Mårup, Lønstrup, northern Denmark.*

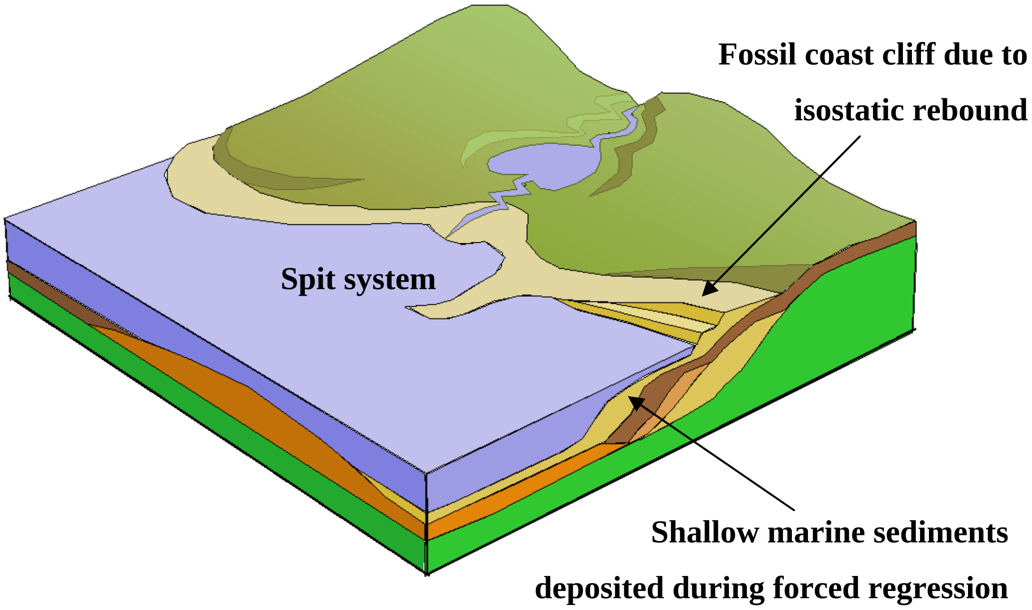

Figure 8. *Block diagram illustrating the transgressive system developing during the melting of the ice. Due to the glacio-isostatic uplift of the land, forced regression influence the system resulting in elevation of former coastal cliffs and shallow marine deposits are exposed above sea level. This dynamic development favours the creation of spit systems and similar marine foreland settings.*

Geological setting of Denmark

Denmark is a lowland with hills generally less than 150 m high (Fig. 9). The main part of the land is characterised by a glacio-morphological topography with fjords incising the former tunnel valleys. The Main Stationary Line forms a characteristic boundary down through Jutland, west of which huge sandur plains and erosional remnants of the Saalian landscape are situated. The most significant addition to the land after the ice age is the Skagen Odder, 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 in press) and is closely related to the main 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. 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 westcoast of Jutland, the western part of Limfjorden had no connection to the North Sea for about 1000 years and ended up with being 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. The island of Mors, which is an important target for the field trip, may be regarded as the remnant island of the eastern part of the former archipelago situated in the western Limfjorden Region.

The Pre-Quaternary Geology of northern Denmark

The geological map of the Danish bedrock is shown in Fig. 10. The geological setting of northern Denmark is related to the main tectonics of the Norwegian–Danish Basin. A very strong element in this setting is the 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 Tornquist Zone took place about 60 mill. years ago, but earthquakes in southern Scandinavia are still concentrated along this zone.

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.

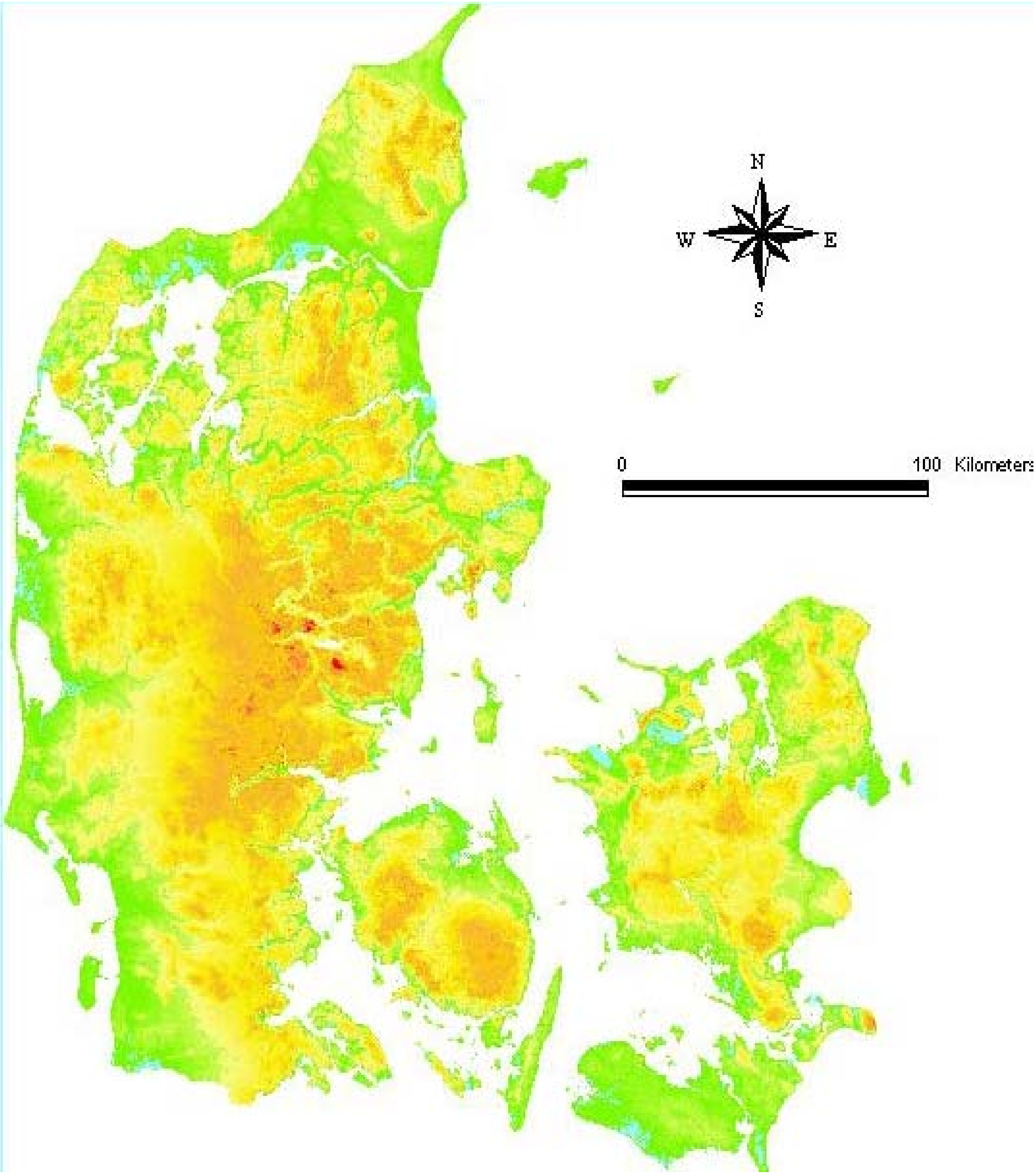

Figure 9. *Geomorphologic map of Denmark .The red dots mark the highest points in Denmark, ca. 150 m above sea level. The shift from brown to yellow areas is anout 100 m above sea level, and the shift from yellow to green is about 10 m above sea level.*

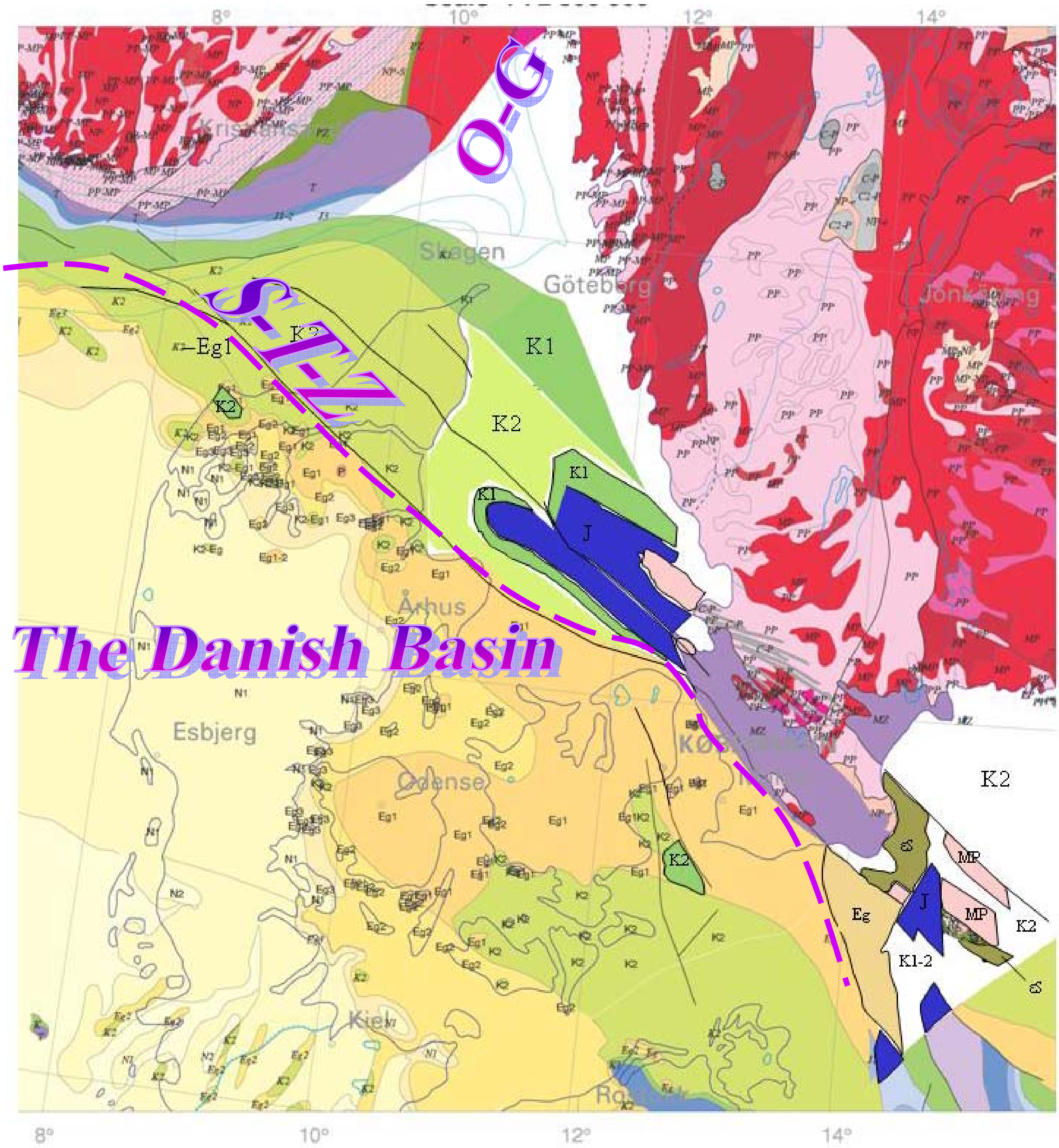

Figure 10. *Bedrock geology of the Danish Basin. To the north and east the Scandinavian basement of Norway and Sweden constitute the margins, here shown in red colours, which represent gneisses and granites about 1500 mill. years old. The green colours represent chalk of Cretaceous age (K1 & K2). The light orange-brown colour shows the distribution of the Danian limestone, and the lighter beige colours are Tertiary clay and sand with lignite. The Sorgenfrei-Tornquist Zone (S-T-Z) is a SE–NW trending fault zone, which cuts the NE part of the Danish Basin. Along this zone large displacements took place 60–50 mill. years ago contemporaneous with the formation of the Alps. O–G is the Oslo Graben, where volcanism was active in the Permian.*

In the Permian period (ca. 270 mill. years ago) strong volcanic activity affected the Oslo Region during the tectonic activity that created the Oslo Graben. The lava succession with rhomb porphyries form the impressive mountains along the Oslo Fjord, and among the related plutonic igneous complexes the Larvikite is very famous. In the same period the northern part of Denmark was a shallow sea situated in tropical environment, which resulted in deposition of thick salt layers. Above the salt layers red sandstones were accumulated in the arid Triassic period in a succession about 3–4 km thick. The salt diapir province of the western Limfjorden Region can be recognized as the complex structural pattern in the north western part of Denmark typically outlined by a spot of Cretaceous rocks surrounded by a circle of younger sediments (Fig. 10). The detailed locations of the individual salt diapirs are shown in Fig. 5, and similar information can be seen in the geological map of the bedrock geology in northern Denmark. It is almost evident that the salt diapirs and pillows played a guiding role in the present formation of the landscape in the western Limfjorden region. The depth to the top of the salt in the Mors salt diapir is 712 m below ground level, whereas the depth to the salt layer east of the diapir is 6 km. In the Batum salt diapir the depth to the top of the salt diapir is only 154 m and also here the salt layer surrounding the diapir is at a similar level 5–6 km below surface. A very good example of a salt pillow structure is the Thisted Structure, although the depth to the salt is about 3 km the elevation of the chalk as shield is very remarkable, because it creates a huge horseshoe pattern outlined by the chalk ridges in the area between Hanstholm and Thisted.

At the end of the Triassic period a world wide sea level rise took place, which resulted in the deposition of the Jurassic clays known as source rock for many oil deposits in the North Sea, and later the huge carbonate platform extending over most part of northern Europe during the Cretaceous period, which terminated at about 65 mill. years ago. In the northern part of Denmark the loading of the up to 6 km thick pile of sedimentary rocks above the salt, combined with strike-slip displacement along the Sorgenfrei–Tornquist Zone resulted in salt migration. A number of salt diapirs were created, which lifted the Cretaceous rocks up into dome like features (salt horsts) and depressions were created between the salt structures serving as depocentres for the Tertiary sedimentation.

The Quaternary geology of Denmark

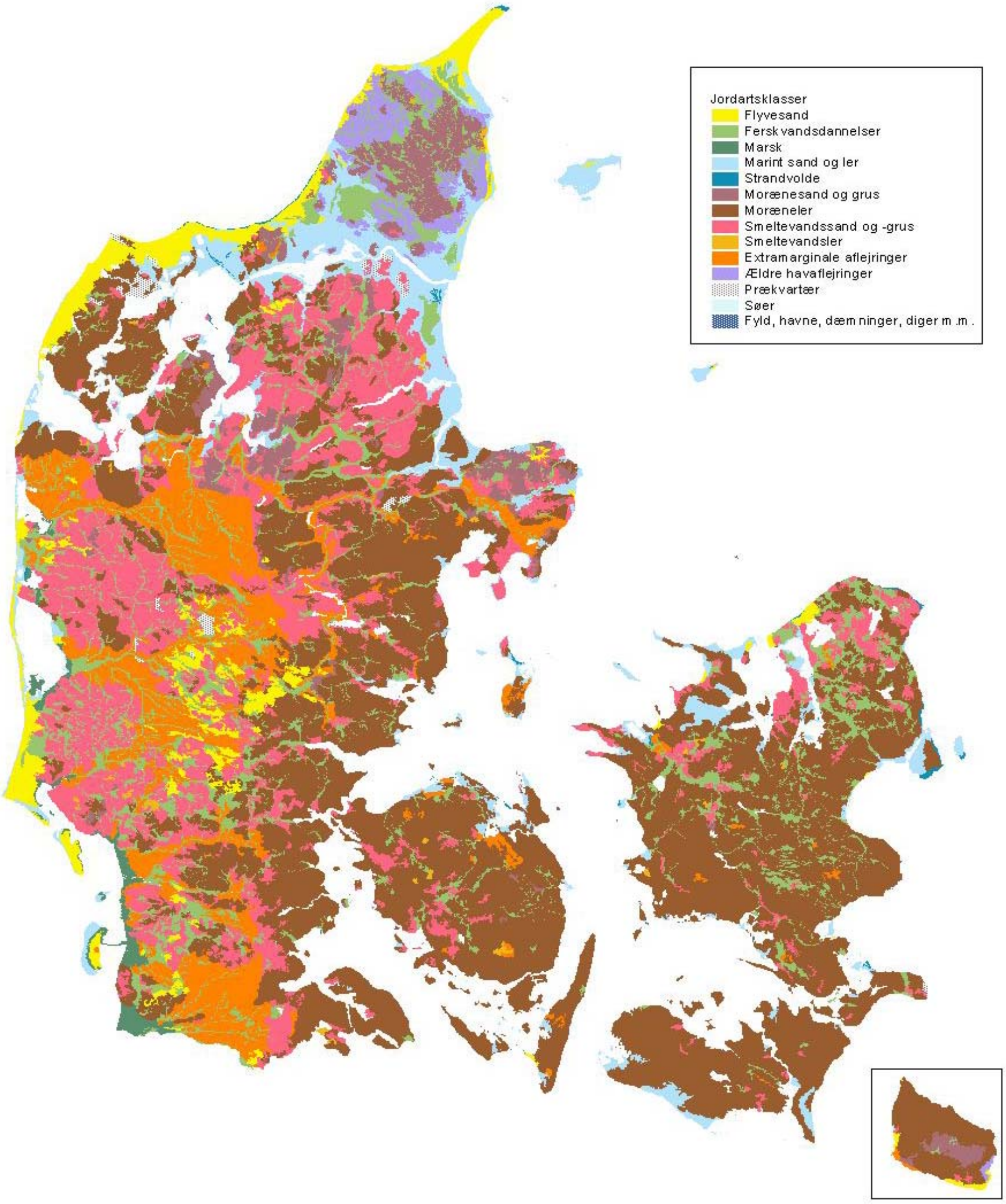

Figure 11. *Geological map of the Quaternary deposits in Denmark. Brown colours are till deposits, mainly deposited as lodgement till by the Norwegian, Swedish and Baltic Ice Streams 30 000–20 000 years ago. Red colour is glaciofluvial sediments older than the last ice advance. Orange colour is melt water sand and gravel deposited on the outwash plane in front of the Main Stationary Line. Violet colour is the 17 000 year old elevated marine deposits known as Yoldia Clay. Blue colours are elevated Holocene marine deposits; green colour is the fresh water deposits in the drainage systems and peat bogs. Yellow colour represents the aeolian dune sand deposited along the West-coast. From Pedersen, S.A.S. (1989): Danmarks Jordarter, målestok 1:200 000. Danmarks Geologiske Undersøgelse.*

The surface geology of Denmark is dominated by glacial deposits (Fig. 11). During the peak of the last glaciation the northern and eastern part of Denmark was subjected to two large ice advances, one coming directly from the north, the Norwegian Ice Stream, and the other advancing from the northeast, the Swedish Ice Stream. The latter is also known as the NE-Ice advance, which reached the maximum limit of ice transgression during the Weichselian. West of the Main Stationary Line (Fig. 12) outwash plains were formed, which surrounded the hill island landscapes of Saalian age. During the last 5.000 years of the Weichselian the ice advance from the Baltic area dominated the glaciogeological settings in the south and eastern part of the Danish Basin.

North of Limfjorden the flat fields on the horizontal plane represent the glacio-isostatical elevated sea beds from the 17 000 year old Yoldia Sea, and on the margin of Limfjorden elevated sea beds from the Stone Age covers large areas. Along the west coast aeolian dunes cover the coast-near belt, and the northern-most spit of Jutland is built out by beach gravel similarly covered by aeolian dunes (Fig. 11).

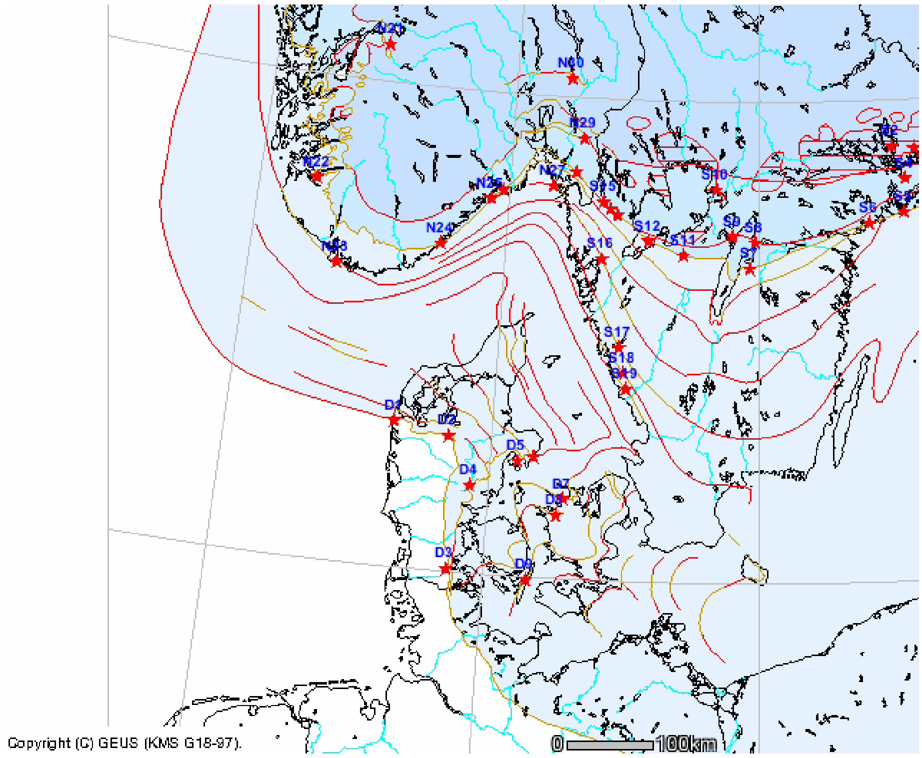

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Figure 12. *Map outlining the Main Stationary Line (MSL) and the subsequent ice margin lines during the retreat of the Scandinavian Ice Cap. The MSL was evacuated about 20.000 years BP and the shift between light and dark blue colours represent the Dryas Line, which formed where the ice melted back to the central part of Scandinavia about 10.000 years BP.*

The geological excursion

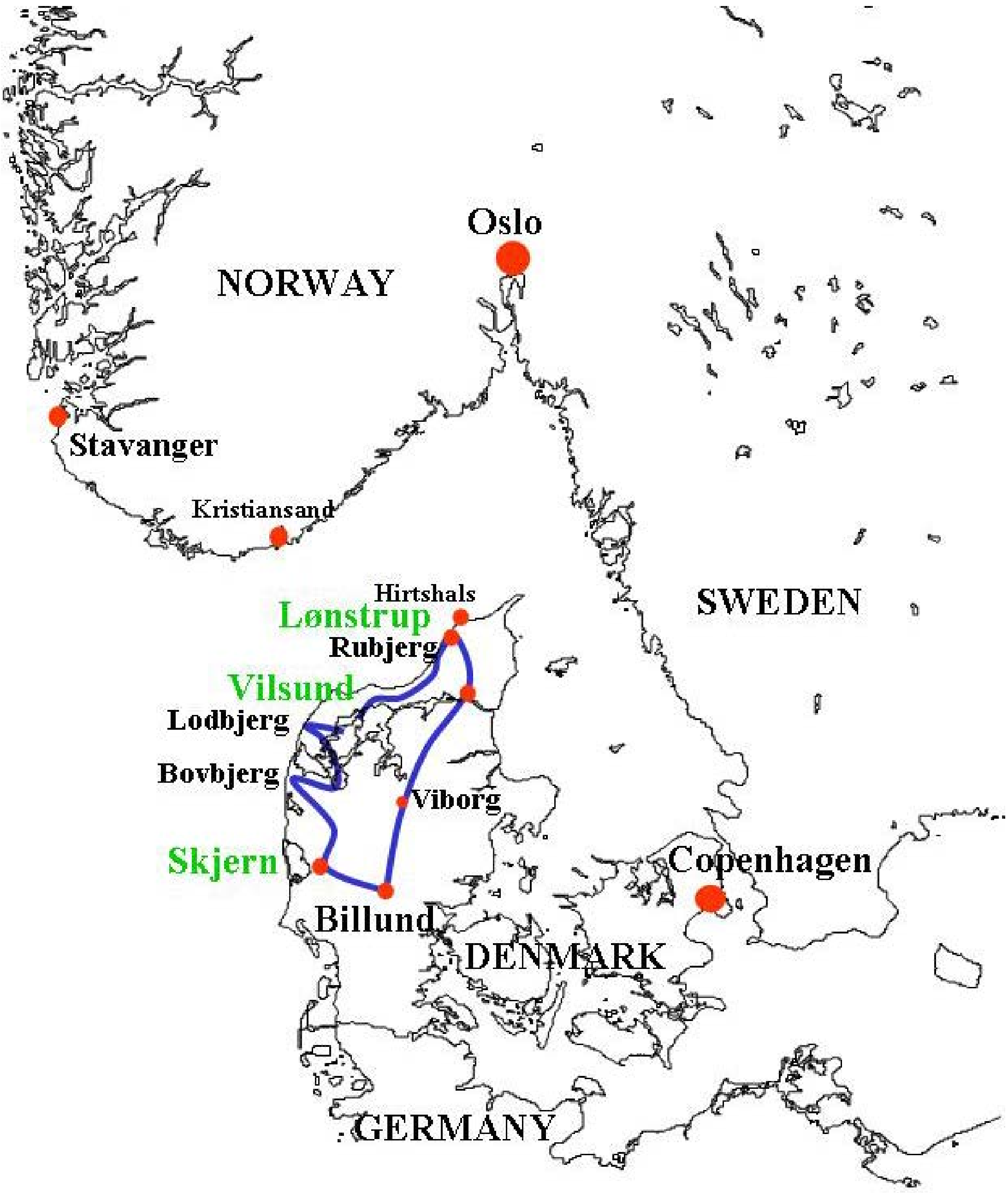


Figure 13. *Route map with important towns indicated in red, the route is marked with a blue line, accommodations are indicated by green names, and some of the key localities are listed as well.*

Outline of the excursion route

First excursion day

The excursion starts at the airport in Billund, central part of Jylland, late in the afternoon March 9th (Cimber Air flight arrives 19.30 from Gatwick, London). From Billund the excursion starts in hired cars heading for the overnight accommodation in the small town Skjern, close to the Ringkøbing Fjord at the estuary of Denmark's second largest stream Skjern Å.

Second excursion day

The next morning the excursion visits two gravel pit before lunch time. These gravel pits are located in the Saalian landscape known as Skovbjerg Bakkø, which is a preserved glacial setting from the maximum impact of the Pleistocene glaciation about 300 000 years BP. Lunch will be purchased during the trip and will be enjoyed at an old Miocene lignite pit, Abildå, close to the last gravel pit location. After lunch the focus will be the impressive c. 4 km long cross section at Bovbjerg along the West Coast, where the Main Weichselian Stationary Line is exposed. This exceptional cross-section displays the transition from the glacio-morphologial landscape dominated by till deposits into the outwash plain landscape characterised by glaciofluvial sediments. Although the glaciofluvial sediments are dominated by proximal deposits, transitions from proximal to more distal facies can be recognized, mainly du to smaller oscillations of the ice margin. The Main Stationary Line was established 24 000 years BP, and the ice melted back about 20 000 years BP. It will be late in the afternoon before this locality can be left, and in the fading daylight we will drive along the Main Stationary Line and see the variation between moraine landscape and outwash plain landscape. While the sun is setting we will be heading north for the accommodation at the cosy old ferry inn Vildsund Færgekro, where we will stay two nights.

The second days morning the locality Lodbjerg will be demonstrated. This is a coastal exposure at the North Sea beach, where drop-till successions can be investigated. The interpretation of these deposits indicates that the sediments were deposited in a not too deep sea with brackish water due to a large discharge of melt water – marine shells are very rare. However, the drop stones can be seen very nicely to have been deposited in the main laminated seabed lithology. From Lodbjerg we will drive back to Vildsund Færgekro for lunch.

The focus of the afternoon’s excursion will be glaciofluvial gravel developing into glaciolacustrine sediments and various clayey till deposits. Moreover, one of the most impressive glaciotectonic settings will be demonstrated, where an Eocene clayey formation, about 60 m thick, has been thrust and laterally translated more than 250 m over the foreland constituting glacigene deposits. At the end of the day we will visit some clay pits to look at the transition from glacitectonites into lodgement tills.

Figure 14. ***The Hanklit thrust fault complex****.A thrust sheet comprising a 60 m thick unit of Eocene diatomite has been translated more than 250 m over the foreland of glacigene deposits.*

Third excursion day

The target of the third excursion day will be to walk the 6 km long coastal cliff section of Rubjerg Knude at Lønstrup in northern Jutland. However, first we have to drive 1½ hour from the Limfjorden, where we have stayed two nights at Vildsund Færgekro, to north-western part of Vendsyssel. Here we will start the excursion of the day at Nr.

Lyngby, where the foreland of the Rubjerg Knude Glaciotectonic Complex is situated, and from where we will go through the development of the glaciotectonic complex and its lithologies.

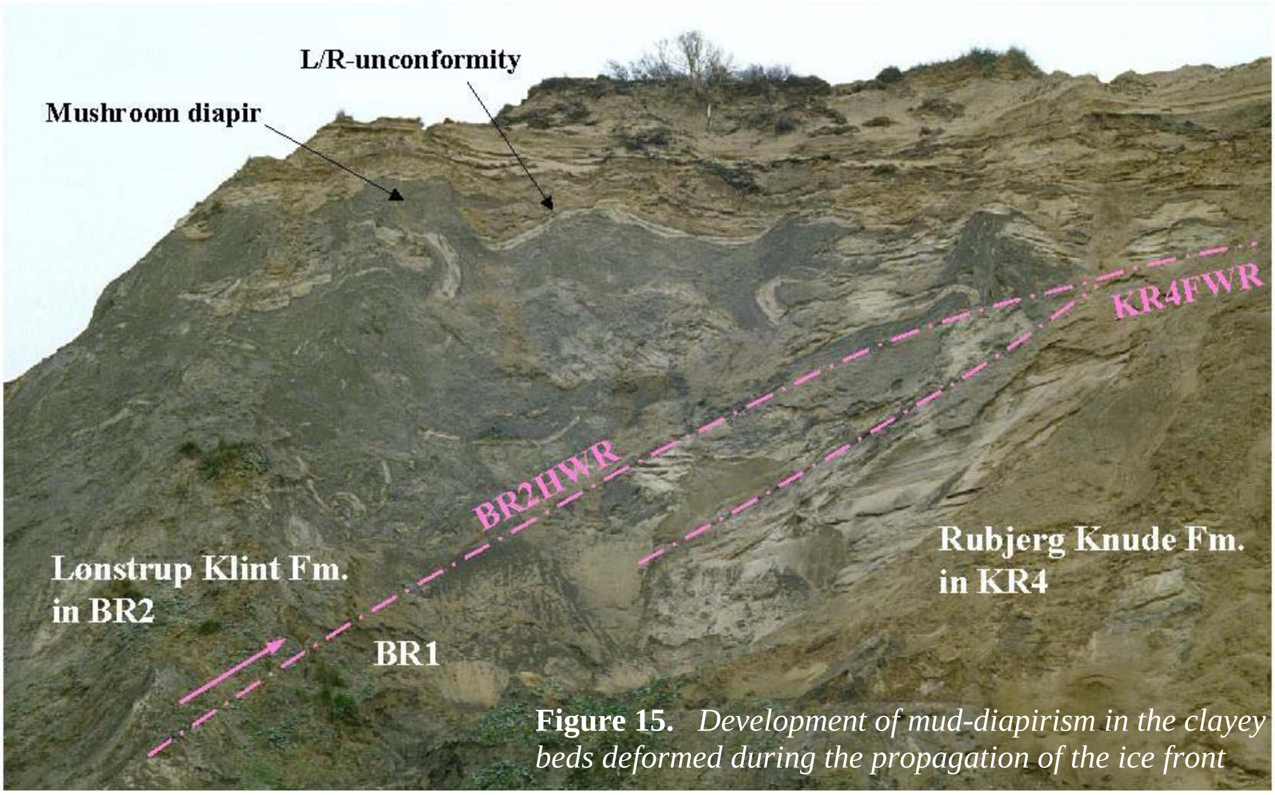


Figure 15. *Development of mud-diapirism in the clayey beds deformed during the propagation of the ice front*

A number of various lithologies and structures are here displaced. We will study primary structures with beautifully developed climbing ripples, we will study ball- and pillow formation, and we will see some of the most spectacular hydrodynamic breccias, from small flame structures and up to 20 meter high mud diapirs. The older Arctic marine sediments are exposed in the central and northern part of the complex, where they form décollement zone of the glaciotectonic thrusting. The post glaciotectonic arctic marine sediments (Younger Yoldia Clay) are exposed south and north of the complex, where they on-lap the hill island created by the glaciotectonic complex. In this formation (Vendsyssel Fromation) we will see examples of the transgression – regression development, tracefossils with preserved *Hiatella arctica* in life position, and traces of ice bergs scouring the sea bed. The day will end at Lønstrup, where we will stay overnight in hotel Kirkedal.

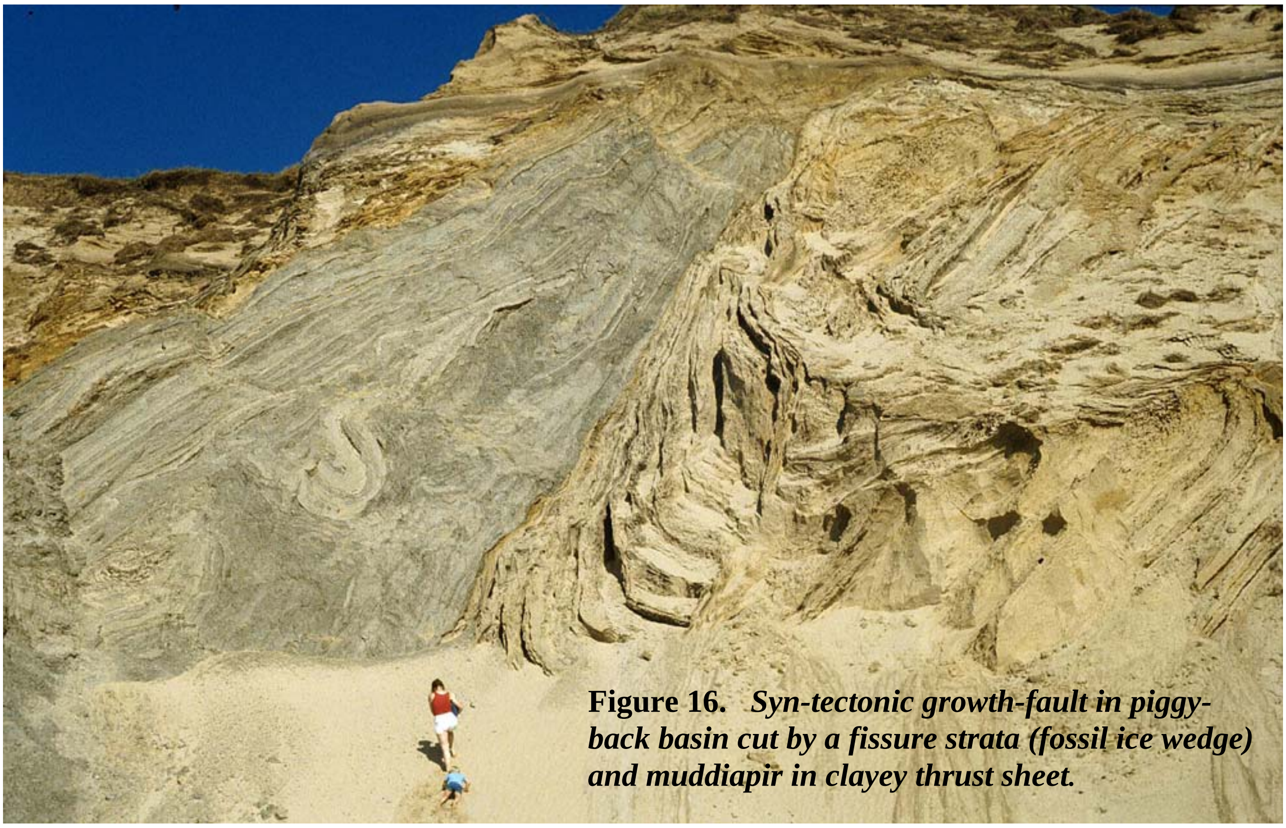


Figure 16. ***Syn-tectonic growth-fault in piggy-back basin cut by a fissure strata (fossil ice wedge) and muddiapir in clayey thrust sheet.***

Last day of the excursion

The drive back from Lønstrup to Billund Airport will take about 4 hours. To make this trip as informative as possible we will drive across the transition from glaciomorphological landscape into outwash plain at the old “classic” tunnelvalley site Dollerup Bakker near Viborg. After having passed the beautiful hilly landscape along Hald Sø and enjoyed a lunch break looking over the heather hills we continue up to Skelhøje, where gravel pits are situated excavating the proximal part of the glacio-alluvial fan known as Karup Hedeslette. Then we will progress southwards and arrive at Billund in due time to reach the plane for London leaving at 15.45.

Description of localities

Loc. 1: Attenager gravel pit

The Attenager gravel pit is located south of the main road between Ringkøbing and Herning, ca. 10 km east of Ringkøbing. In the pit sand and gravel are excavated from the glaciofluvial deposits related to the early Saalian glaciodynamic sequence (Fig. 17). The glaciofluvial succession is representative for the dominant deposits at the Skovbjerg Bakkeø, which is the biggest of the hill islands representing the Saalian deposits and landscapes in western Denmark. A hill island (bakkeø) is an old-fashioned term of a hilly landscape elevating like a turned bowl over the otherwise completely flat outwash plains.

Figure 17. *The Attenager gravel pit. The glaciofluvial succession is more than 30 m thick and the top of the sand and gravel sediments a till with Norwegian indicator boulders occurs.*

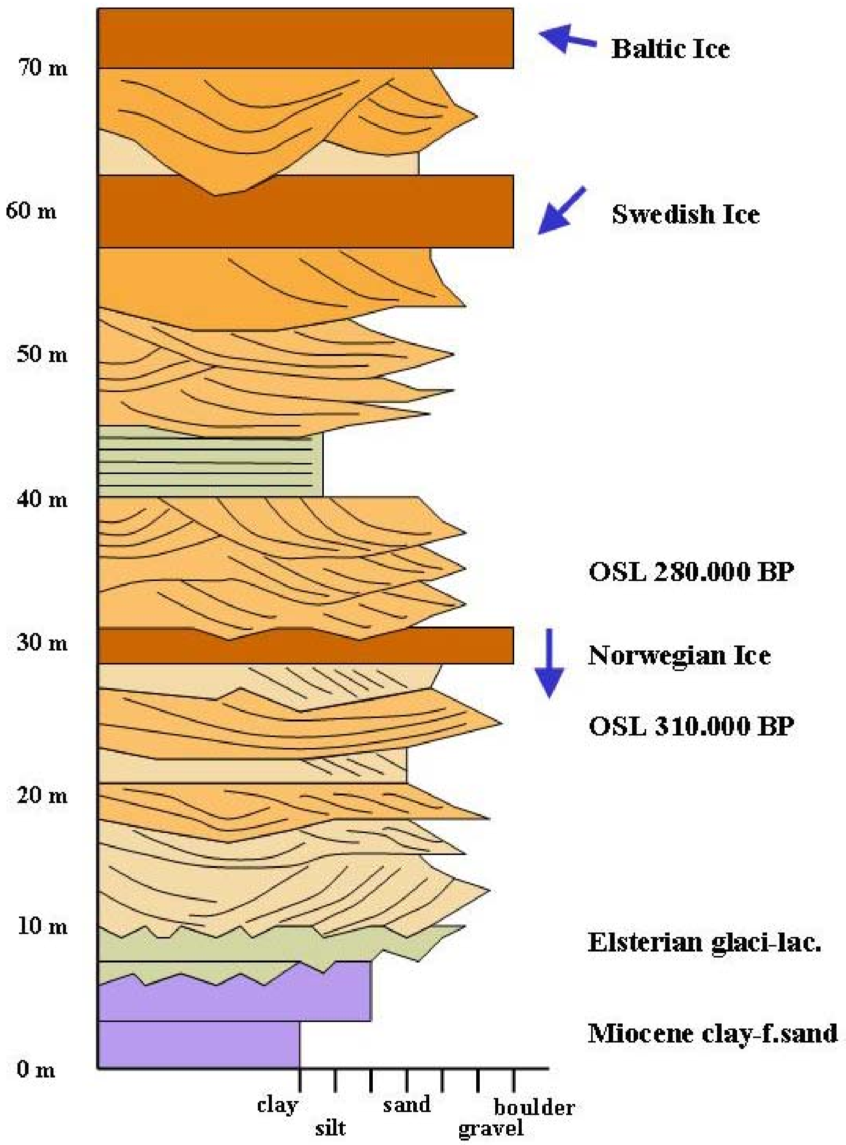


Figure 18. *The geological log of the Saalian deposits constituting the glacial environment of Skovbjerg Bakkeø. The blue arrows indicate the dominant direction of ice advance mainly based on deformation structures in the sediments below the tills. The dating of the oldest ice advance was done by optical stimulated luminescence (OSL).*

The litho-facies to be demonstrated in the Attenager pit are large scale cross-stratification and coarsening-upward glaciofluvial successions (Fig 19). It has been argued that the large-scale cross-bedding is due to Gilbert delta deposition, which might be supported by the presence of climbing ripple stratification at the base of the succession, indicating a glaciolacustrine environment (Fig. 20). In the western part of the pit the glaciotectonic deformation related to Norwegian ice advance is exposed (Fig. 21).

Figure 19. *Large-scale cross-stratification in a glaciofluvial succession at Attenager.*

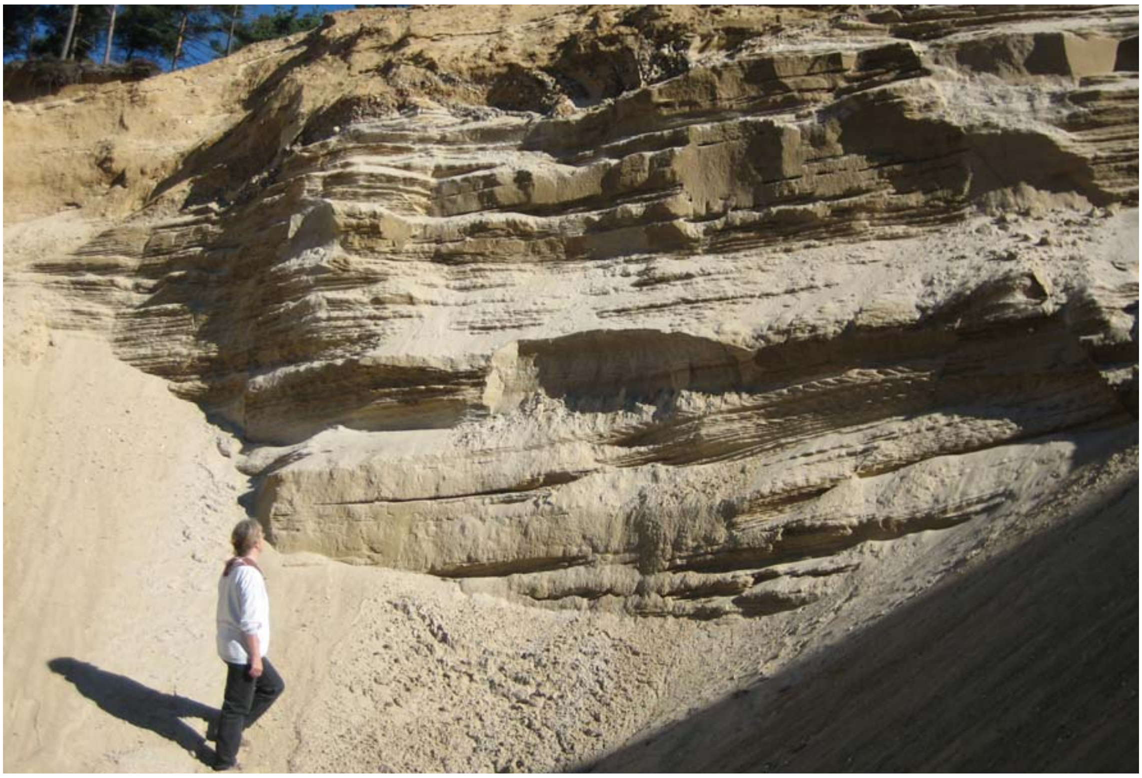


Figure 20. *Climbing ripple stratification in the glaciofluvial sand in the lower part of the succession in the Attenager gravel pit. This indicates a galciolacustrine environment for the setting in the central part of the pit. The formation of the high foresets of the cross-bedding in Fig. 19 is suggested to be related to the same lacustrine basin.*

Figure 21. *Glaciofluvial sediments deformed in a recumbent syncline. The deformation and the till above the deformed beds were both caused by the advance of the Saalian ice with its source in the Norwegian mountains. Details of the fold structures are shown in Fig. 22.*

Figure 22. *The detailed structures in the glaciotectonically deformed glaciofluvial sediments.*

Loc. 2: Grønbjerg gravel pit

‘The Grønbjerg gravel pit is situated 4 km due east of Grønbjerg, a small village in the central part of Skovbjerg Bakkeø. At this locality a 20 m thick succession of glaciofluvial sand and gravel form a outwash fan directed towards the SSW indicating ice advance from the NE (Fig. 23). Furthermore the pit is a cut into the N–S trending hill ridge Fjallene, which reflects neo-tectonic deformation of the Saalian glaciofluvial deposits. Details of the fault structures displacing the sand beds are shown in Fig. 23.

Figure 23. *Glaciofluvial beds dipping gently towards SW in the outwash fan exposed in the Grønbjerg gravel pit.*

Figure 24. ***Small extensional faults displacing the glaciofluvial beds in Grønbjerg gravel pit***

Loc. 3: The Bovbjerg cross-section

The cross-section through the Main Stationary Line (MSL) is beautifully exposed in the coastal cliff at Bovbjerg. The locality is situated about 10 km SW of the town Lemvig (Fig. 25). North of the cliff the little fishing village Ferring is situated, and to the south the Trans Church is located on the top of the cliff. At the highest point in the middle of the cliff section the Bovbjerg lighthouse is a fix point in the landscape.

The Bovbjerg MSL complex comprises three zones: the proximal zone furthest to the north, the central zone, and the distal zone furthest to the south (Fig. 26). The proximal zone is characterised by the accumulation of the till at the margin of the ice. Here more than 20 m of till has been deposited. In Fig. 27 a photo from the recent ice margin in northeast Greenland illustrates the typical environment of the ice margin setting. Note on this photo that the ice already melted back from the push moraine at the stationary line. The central zone is occupied by a glaciotectonic complex, in which the older clayey Saalian till has been thrust up into thrustsheets (Fig. 28). The distal zone comprises the interfingering between tills and glaciofluvial deposits reflecting the oscillation of the ice margin along the MSL (Fig. 29).

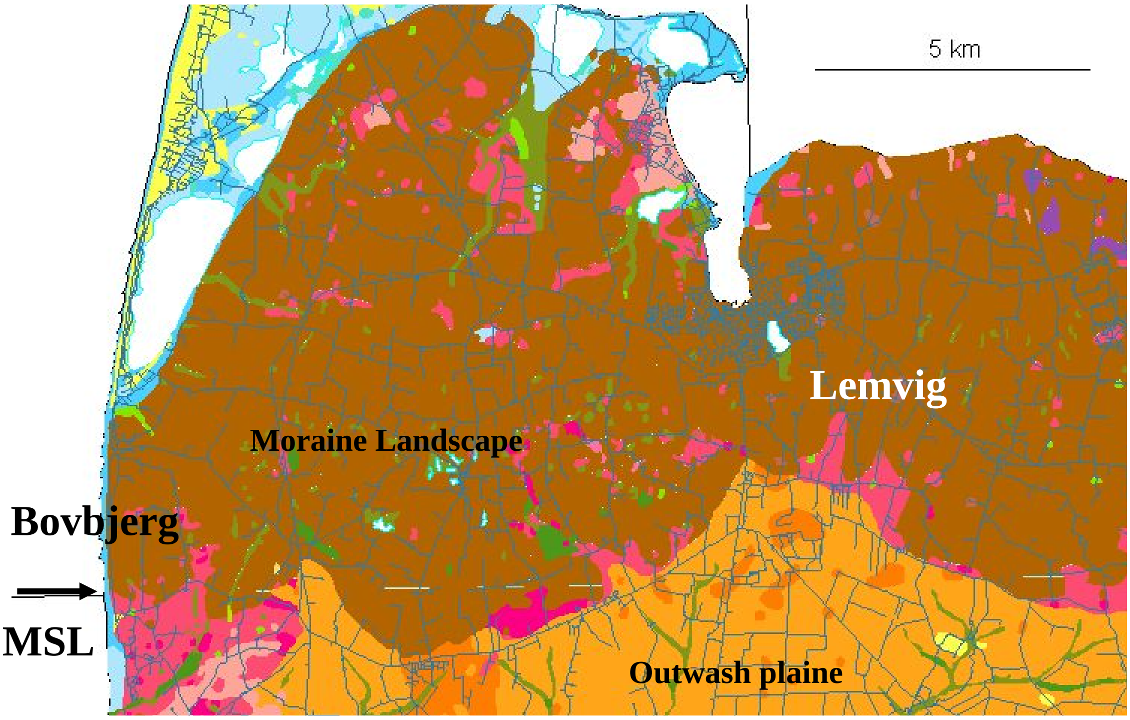


Figure 25. *Quaternary geological map outlining the Main Stationary Line (MSL).*

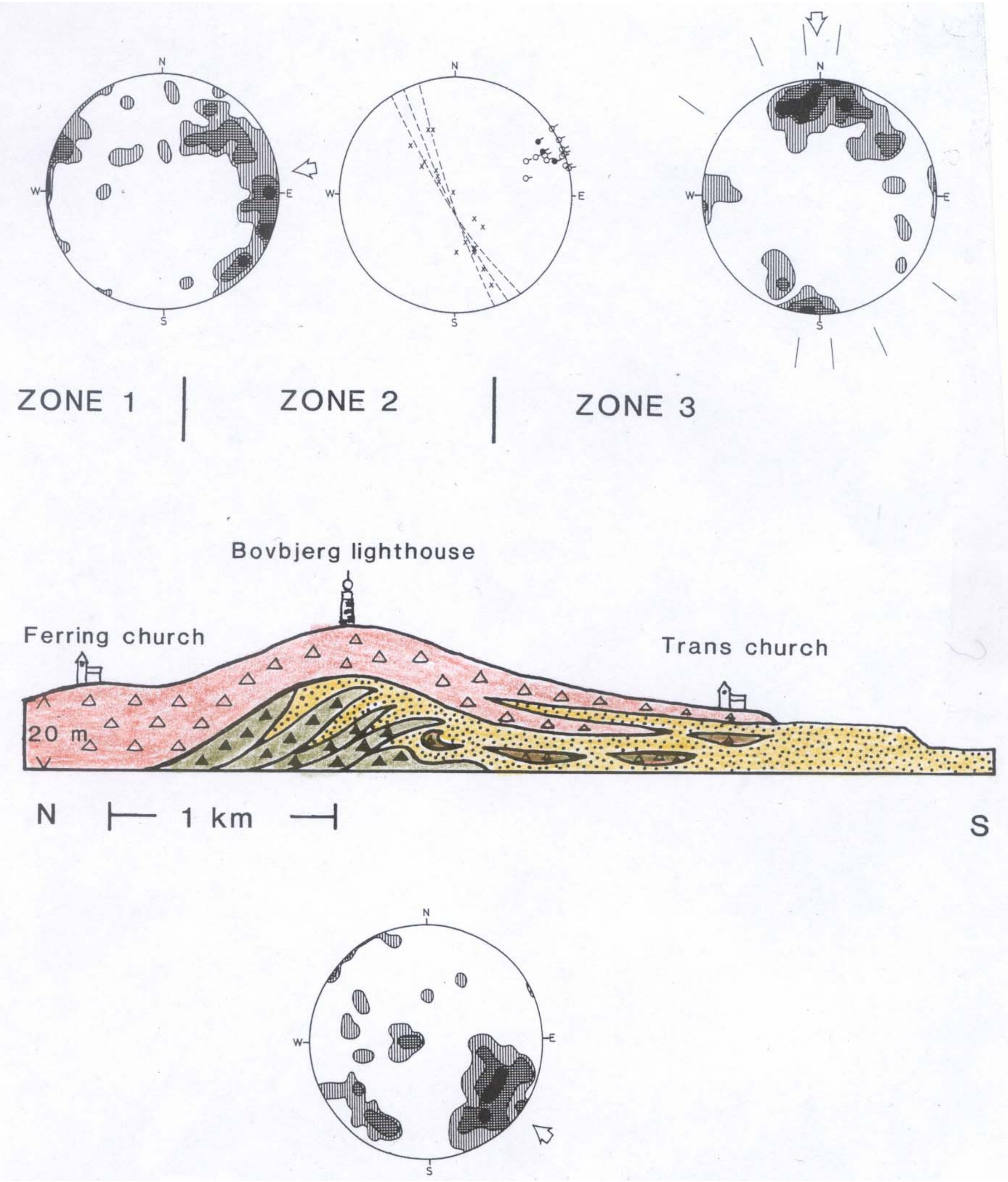


Figure 26. *Simplified geological profile of the Bovbjerg cliff section. The tills are indicated by triangles. The yellow unit with dots is the glaciofluvial beds. The red-brown unit at the top is the till deposited by the Swedish ice advance, the olive green is a Saalian till, and the broken till is from the Norwegian ice advance. The Wulff net represent till fabric analyses. From Pedersen et al. (1988).*

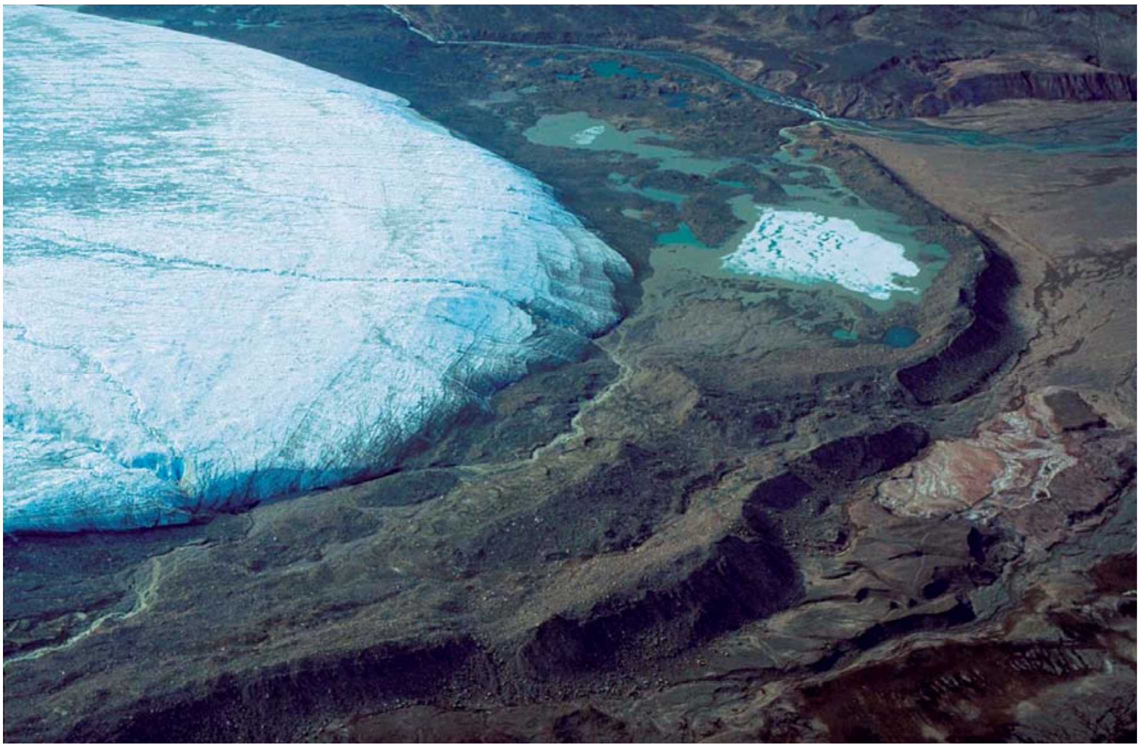


Figure 27. *Ice margin in Kronprins Christians Land, NE Greenland. Note the ridges of marginal moraines, which are about 30 m high. In the space between the retreating margin and the dominant moraine ridge a glaciolacustrine environment is established. The former outwash plain extends out to the right.*

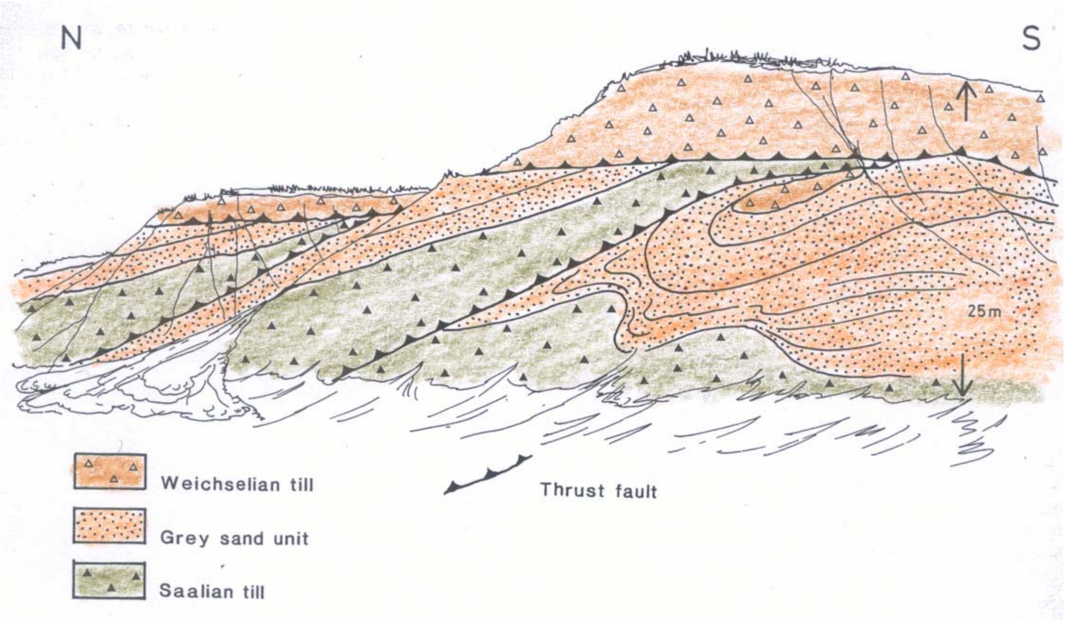


Figure 28. *The glaciotectonic thrust deformation in the central zone of the Bovbjerg profile. From Pedersen et al. (1988).*

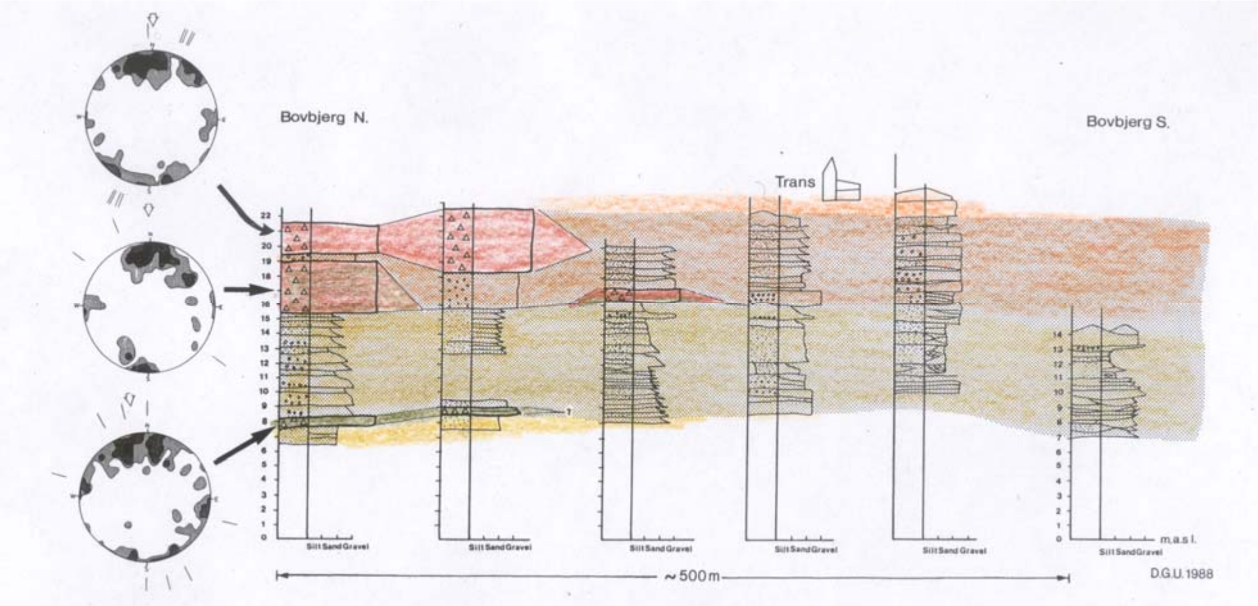


Figure 29. *The interfingering between till and glaciofluvial sand and gravel in the distal zone of the Bovbjerg cross-section. From Pedersen et al. (1988.*

Figure 30. *A cross-section through the glaciofluvial sand and gravel in the southern part of the Bovbjerg cliff section. The deposits here are characterised as proximal deposits in relation to the outwash plain, which extends further to the south (to the right side of the photo).*

Loc. 4: Lodbjerg coastal cliff

The Lodbjerg coastal cliff is situated about 25 km WSW of Vilsund. The landscape here is characterised by the aeolian dunes, which are only a few hundred years old. The coastal cliff shows exceptional good examples of dropstone lithofacies in a setting preceding the ice advance of the Swedish ice about 24.000 years BP.

Figure 31. *General view of the Lodbjerg coastal cliff. The flat topped heads are the glacial deposits, and above the abrasion surface the aeolian dunes are deposited.*

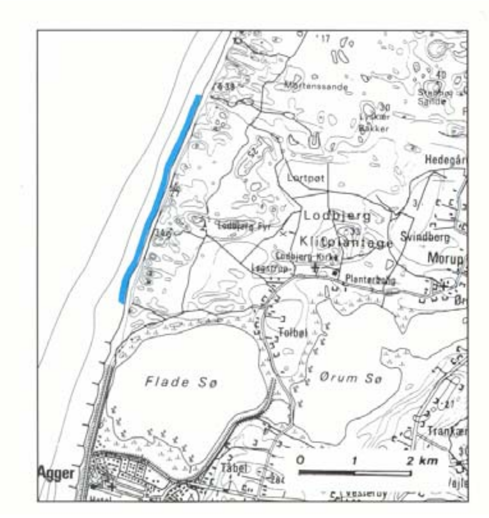
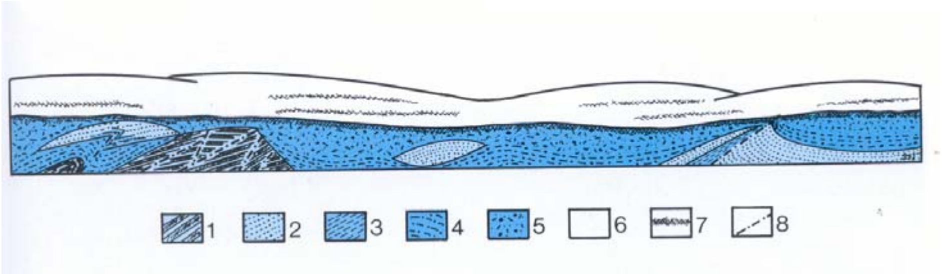


Figure 32. *The detailed map to the left shows the location of the Lodbjerg section, and a sketch of the section is outlined below. 1) is Oligocene dark mud, 2) is glaciofluvial sand, 3) is glaciolacustrine clay, 4) is drop till, 5) is lodgement till, 6) is aeolian sand, 7) is abrasion surface with a soil horizon, and 8) indicates thrust faults. From Andersen & Sjørring 1992: Geologisk set. Det nordlige Jylland. Miljøministerie. SNS.*



Loc. 5. Vilsund coastal cliff

This locality is located about half a kilometre from the Vildsund Færgekro. The cliff section here displays a Saalian till rich in Cretaceous chalk erratic boulders plucked up during the ice advance over the Thisted salt dome to the north. Above the unconformity on top of the till a thick glaciolacustrine sequence was deposited (Fig. 33). This unit has been mapped out during the systematic mapping of the surface deposits in Denmark, and on the geological map (fig. 34) the extent of the unit shows that it form a large lacustrine basin on the northern part of Mors similar to the Limfjorden depression north of the island.

After the visit to the coastal cliff exposure we will drive up into the landscape and follow the glaciolacustrine unit. The unit is occupying the basin in front of the glaciotectonic complex bordering the north coast of Mors.

Figure 33. *The exposure at the Vilsund coastal cliff displays the boundary between the Saalian till below (Hesselbjerg Formation) and the Weichselian glaciolacustrine unit above (Fårtoft unit).*

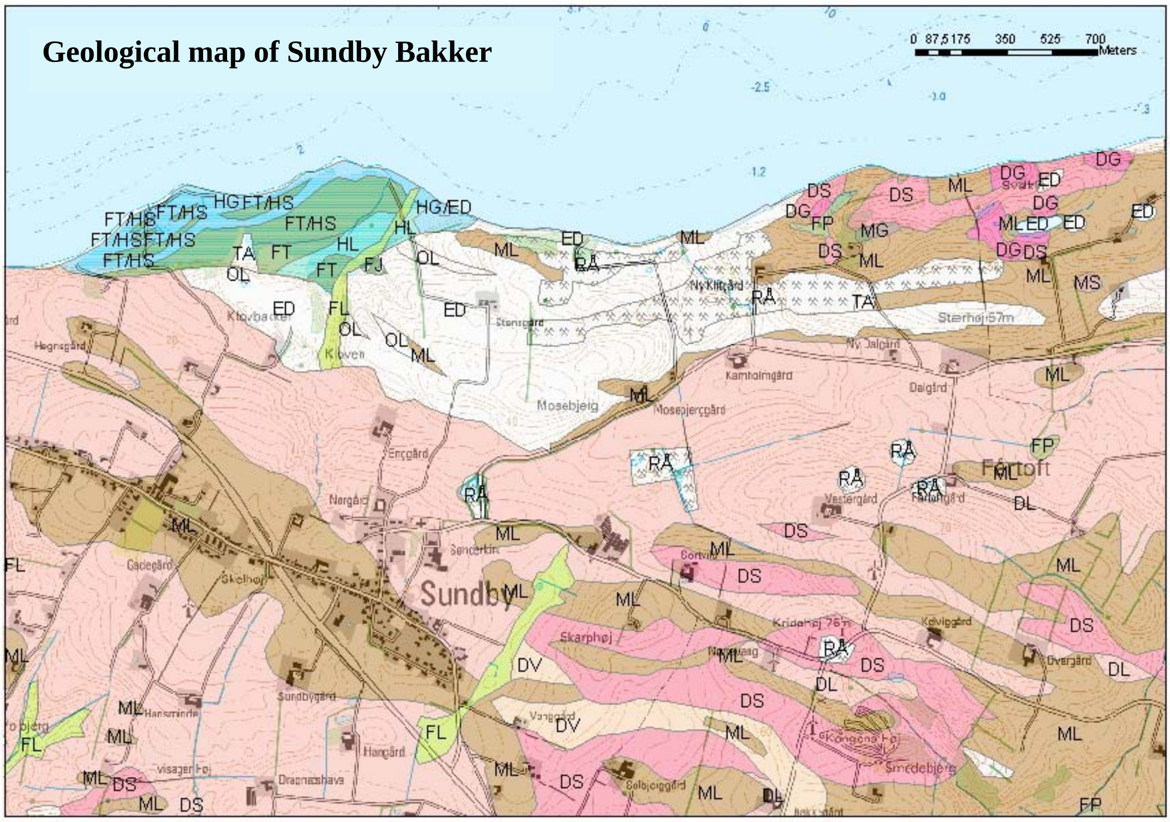


Figure 34. *Geological map of the area east of Vilsund. The pink colour is the glaciolacustrine clay unit (DL), the red colour is glaciofluvial sand (DS), the brown unit is till (ML), and the white unit is Eocene diatomite(ED) thrust up in the glaciotectonic complex along the northern coast of Mors. Green and blue colours are post-glacial deposits.*

Loc. 6: The Hanklit Glaciotectonic Complex

Hanklit is a 60 m high, nearly vertical coastal cliff due north of the village Bjergby. The cliff section gives an impressive view into the interior structures of the parallel ridges landscape on northern Mors (Fig. 35). Here the Eocene diatomite with volcanic ash layers known as the Fur Formation has been displaced along a thrust fault for more than 250 m (Fig. 14). The thrust sheet is 60 m thick and the uppermost ca. 15 m comprises a glaciodynamic sequence of fining upward gravel, sand and clay at the top. This clay correspond to the Fårtoft unit previously seen. A balanced cross section of the structures is shown in Fig. 36.

Figure 35. *The Hanklit cliff display an impressive cross-section of the composite ridge system related to the glaciotectonic complex on northern Mors.*

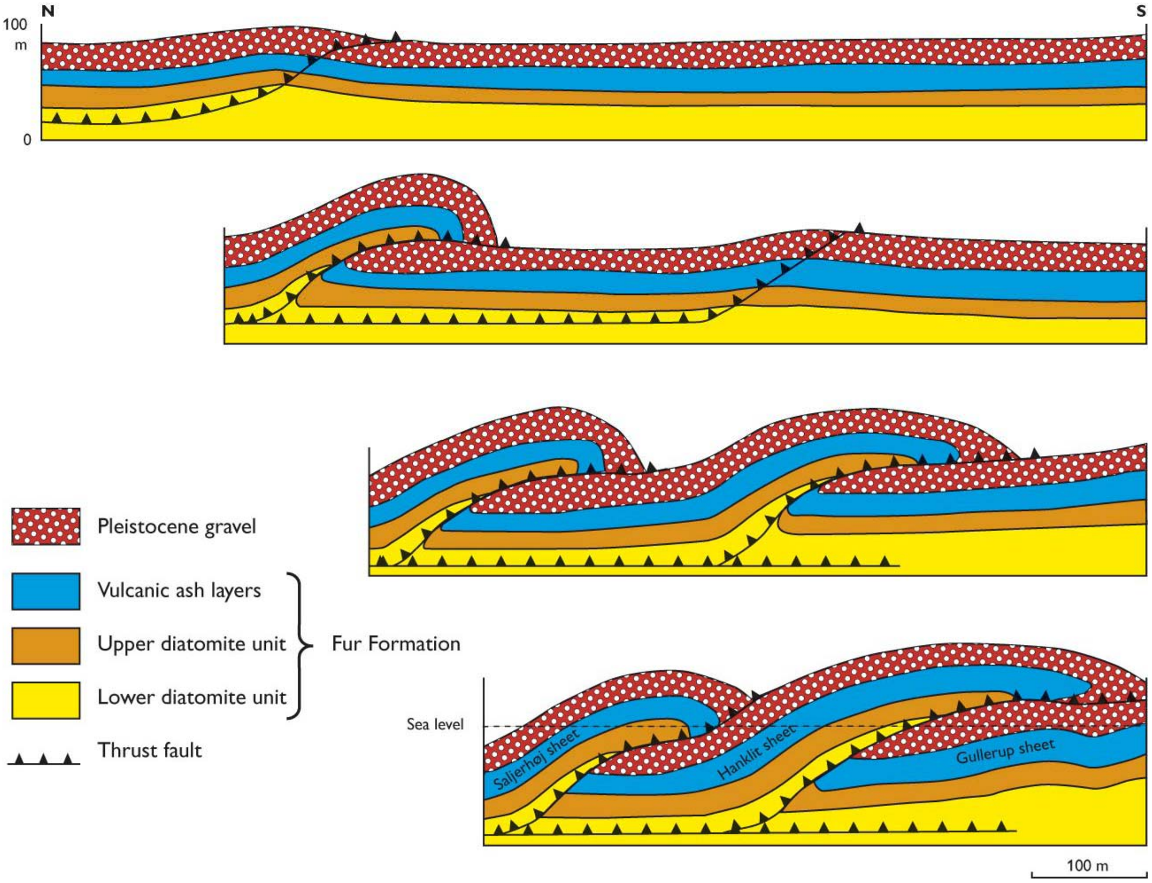


Figure 36. *The balanced cross-section of the Hanklit Glaciotectonic Thrust Fault Complex.*

Loc. 7: Feggeklit coastal cliff section

The northernmost part of Mors is a peninsula named Feggeklit. Along the east coast of this former island, now connected to the main island by post-glacial marine sediments, a classic cross-section displaying glaciotectonic folds is located. The folds are very instructively outlined by the Eocene volcanic ash layers in the light diatomite (Fig. 37). A simplified model for their formation is illustrated in Fig. 38.

Figure 37. *The glaciotectonic folds in the Feggeklit cross-section.*

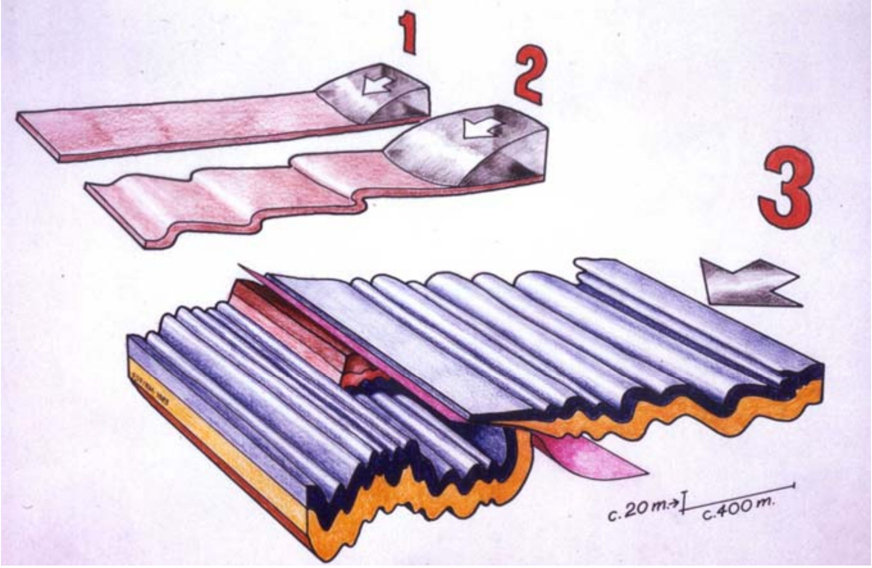


Figure 38. *Simplified model for the formation of glaciotectonic folds in the Feggeklit cliff.*

The Nr. Lyngby coastal cliff locality

The southernmost locality at Lønstrup Klint cliff section is Nr. Lyngby, a summerhut village 5 km north of Løkken. Here a neo-tectonic fault is exposed, which displaces the glacio-marine shallow sediments included in the Vendsyssel Formation (Fig. 39).

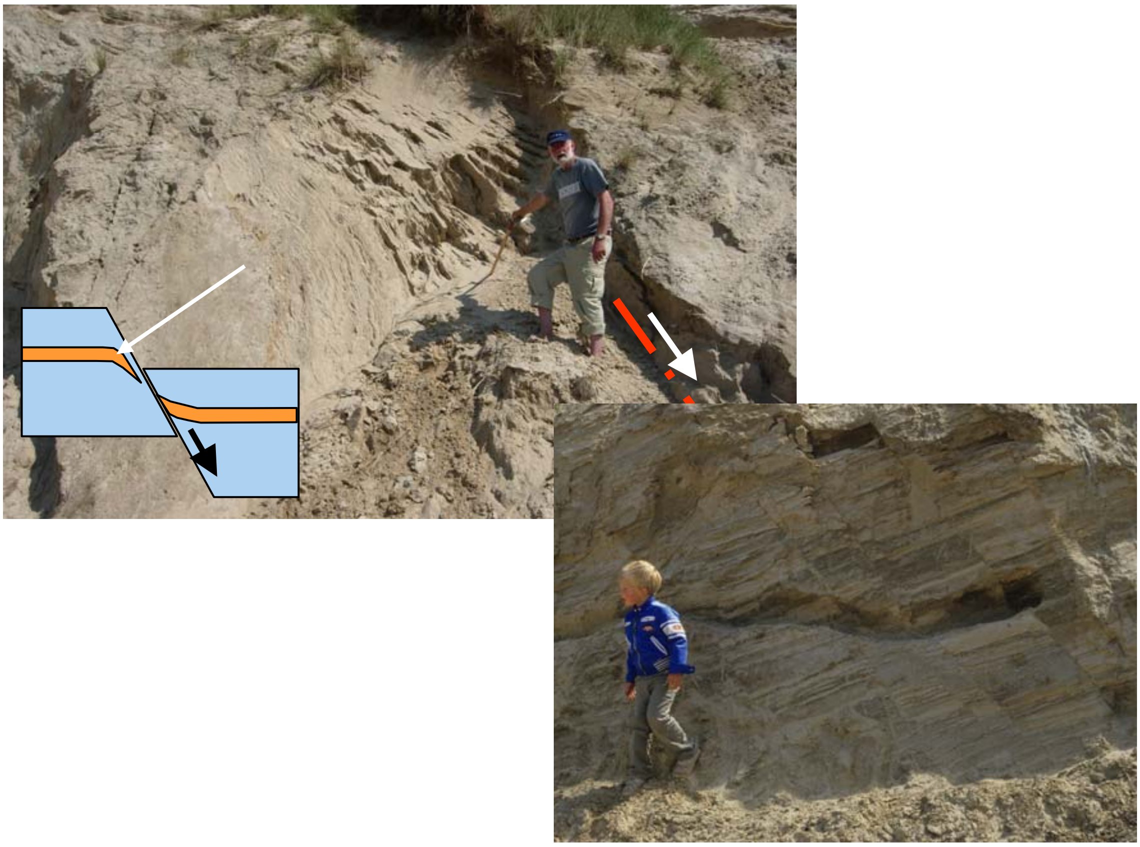
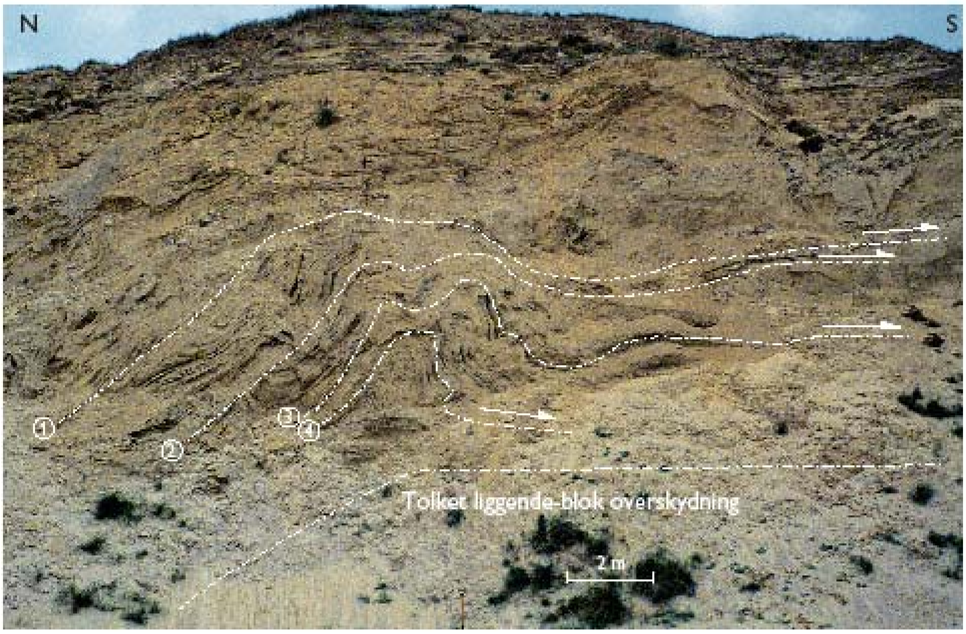


Figure 39. *The Nr. Lyngby fault zone. The upper photo shows the foot-wall block and the drag along the normal fault plane. The lower photo shows a network of extensional faults in the hanging-wall block. The displacement along the fault is ca. 25 m, which enables to study the uppermost part of the glacio-marine Vendsyssel Formation in the downthrown block as well as the lowermost part in the foot-wall block. The fault is truncated by deposits of the Allerød bog sediments, which dates the fault to be active between 15.000 and 11.700 BP.*

Loc. 9: Stensnæs, southern part of the Lønstrup Klint cliff

One of the most spectacular localities in the southern part of the Rubjerg Knude Glaciotectonic Complex is the folded structures at Stensnæs. The folding here is created due to the combination between hanging-wall anticlines formed over the ramp hinge and ramp collapse during thrust fault propagation (Fig. 40).



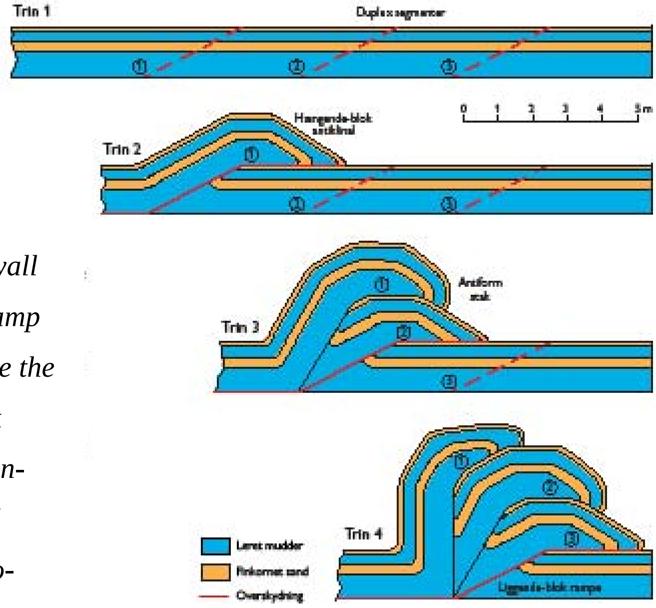


Figure 40. *The hanging-wall anticlines formed during ramp collapse at Stensnæs. Above the fold structures a piggyback basin was formed which contains big rafts of the tips of thrust faults propagating towards the foreland.*

Loc. 10: Rubjerg Knude, central part of Lønstrup Klint cliff

At the highest point of the cliff section Rubjerg Knude is situated. On top of the cliff the lighthouse was erected I 1900, which has now been nearly covered by aeolian sand. In the coming few year the lighthouse will fall in to the sea due to the main coastal erosion of 1.25 m per year. Below the lighthouse the deepest level of thrusting is present, which enable us to study the glacio-marine sediments deposited prior to the late glacial maximum in the Weichselian. These sediments are characterised by dark bluish to black mud with abundant content of dropstones and rich in arctic mussels (Fig. 41).

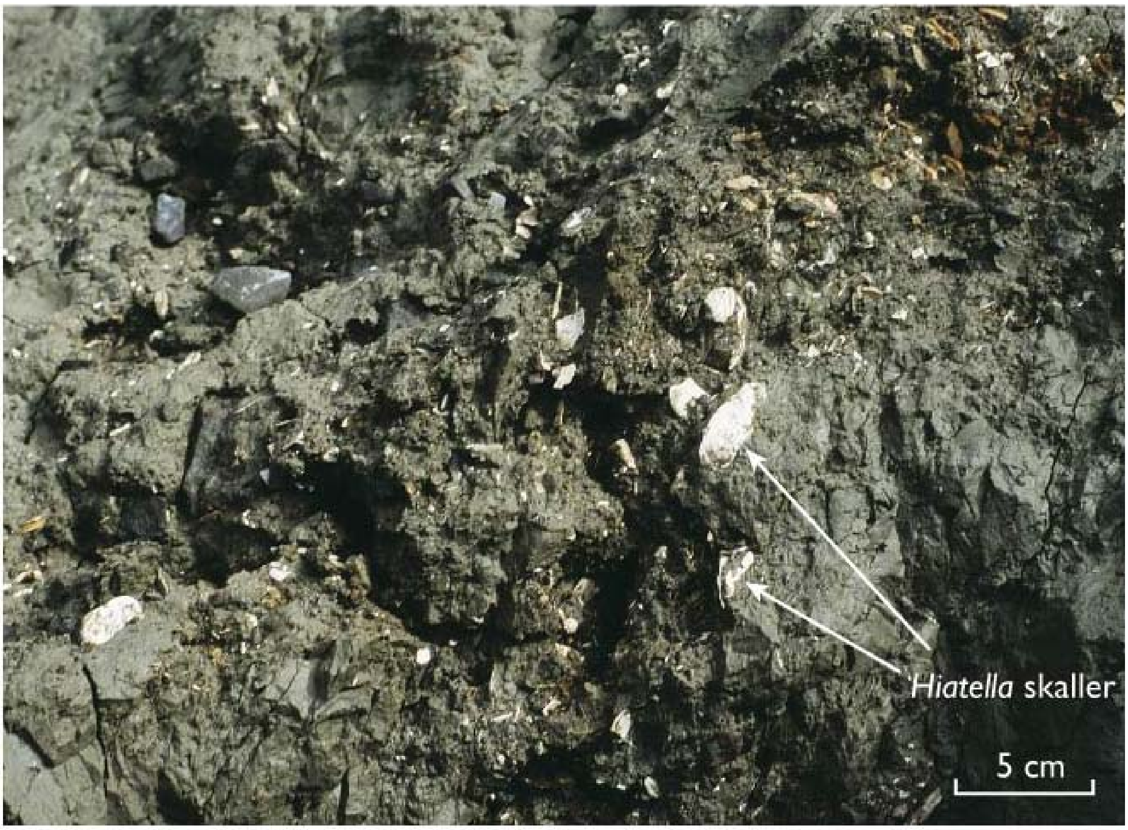


Figure 41. *The Hiatella arctica mussels in the dark muddy glacio-marine sediments included in the Stortorn Formation. This formation is the lowermost unit exposed at the surface and it is included in the Skærumhede Group, which provide sedimentary records from the beginning of the Weichselian. The shells have been carbon 14 dated to about 31.000 years BP.*

Loc. 11 Ribjerg–Mårup, northern part of Lønstrup Klint cliff

Between the Mårup Church and the hill Ribjerg at Lønstrup the late Weichselian glacio-marine successions are very well exposed. However, they cliff might be difficult to get access to due to the muddy lithologies, or the outcrop can be hampered by landslides (Fig. 42). At the base of the formation, the Vendsyssel Formation, the fine-grained mud reflecting the highstand situation immediately after the eustatic sea level rise (Fig. 43). When the forced regression takes over the sand deposits gets more and more dominating, and storm sand beds becomes frequent. In the storm sand beds escape traces of *Hiatella arctica* can be recognised, often with shells sitting in “life position” (Fig. 44).

Figure 42. *The cliff section north of Mårup Church. This is one of the reference localities for the formal erection of the Vendsyssel Formation. Note the transition form the dark muddy sediments at the base of the formation (the broad line outlined by the shadow), and the development up through the succession to more and more sandy (light coloured) sediments.*

Figure 43. *Dark coloured, laminated sediment at the base of the Vendsyssel Formation at the reference section north of the Mårup Church.*

Figure 44. *The sandy sediments in the uppermost part of theVendsyssel Formation at Mårup. Note the wavy lamination interpreted as storm sand layers in the shallow marine deposit.*

Loc. 12: Børglum Kloster

Børglum Kloster is situated on top of a hill island in the Yoldia Sea deposits. From the wind mill there is a beautiful view over the landscape with the elevated marine levels and fossil coastal cliffs (Fig. 45).

Figure 45. *The Børglum Klosterat the top of the Børglum hill island. Just in front of the kloster and the wind mill the old fossil coastal cliff created by the Yoldia Sea is situated. The flat part of the roadpasses over the elevated top of the Vendsyssel Formation.*

Loc. 13 Dollerup Bakker and Hald Sø

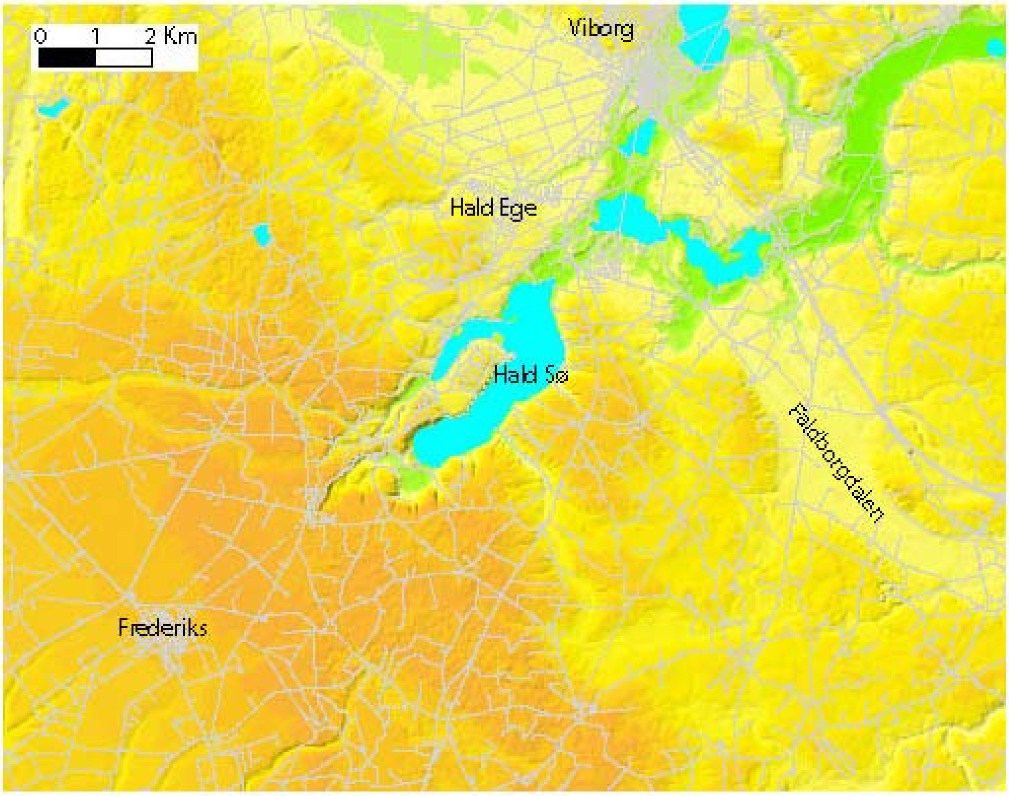


Figure 46. *Topograpic map of the Hald Sø and Dollerup Bakker. The tunnel valley terminated at the SW-end of Hald Sø, from where the outwash plain started and a fan of glaciofluvial sediments were deposited towards Frederiks to the west.*

Figure 47. *View over Hald Sø towards the town of Viborg.*

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PROGRAM

The excursion is a 5 days trip by car to various localities, where no extraordinary equipment is necessary, except for rain clothes and rubber boots in case of a rainy period, and warm clothes because early March is also late winter.

9 March, Monday 7.45 (p.m.): Departure from Billund for overnight stay in Skjern.

10 March, Tuesday 09.00 (a.m.): Excursion from Skjern over Skovbjerg Bakkeø to Bovbjerg. End of day at Vildsund Færgekro for accommodation. We will stay two nights at Vildsund Færgekro.

11 March, Wednesday 9.00 (a.m.): Excursion to Lodbjerg and Mors.

12 March, Thursday 08.45 (a.m.): Departure from Vilsund at Limfjorden and drive to the coast between Løkken and Lønstrup. Excursion along Lønstrup Klint studying Rubjerg Knude Glaciotectonic Complex. Accomodation at Hotel Kirkedal, Lønstrup.

13 March, Friday 9.00: Return trip via Viborg and the Dollerup Bakker – Skelhøje transition to Billund Airport. Connection to London at 3.45.

Adresses for accomodation:

1. **Hotel Vestjyden, Skjern,** Bredgade 58, DK 6900 Skjern,
   phone +45 97 35 13 11
2. **Sallingsund Færgekro,** Sallingsundvej 104, DK 7900 Nykøbing Mors,
   phone +45 97 72 00 88.
3. **Hotel Kirkedal,** Mårup Kirkevej, Lønstrup, DK 9800 Hjørring,
   phone +45 98 96 09 95.