DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/33

Investigation of test sites for a drilling system developed by Badger Explorer ASA

Recommendations of test sites for Badger Explorer's drilling system in the Tertiary deposits of north-western Denmark

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Contents

List of Figures

Introduction

Badger Explorer ASA has developed a unique exploration drilling system, which consists of an autonomous rig-less drilling device, which drill and bury itself in the underground. The drill system is constructed for logging and collecting data by remote sensing aiming at being an elegant tool for exploration for hydrocarbons.

Figure 1. *Badger Explorer ASA is an exploration drilling company settled in Stavanger, Norway. This report is provided for the company for their investigation and testing of a new drilling method.*

In the final development phase, where a full scale system functions test on land is carried out, it is important to test the system in realistic and relevant sedimentary rocks. Therefore, in addition to an artificial test bench-jig in Stavanger, a full scale integrated device will be assembled and a subsurface onshore test will be performed.

In the search for an ideal test site for performing an onshore test, the attention focuses on the northern part of Denmark, where sedimentary rocks of Tertiary age crop out. These sedimentary rocks are comparable to the sedimentary rock units, which are met with in the upper column of the geological sequences, the drilling tool aims at penetrating in the off shore exploration. Badger Explorer ASA has consequently contacted GEUS for assistance and information about the geological settings, technical and practical advices for an onshore drill test operation.

The aim of this report

This report provides an introduction to the geological setting of northern Denmark with the focus on an appropriate test site for drilling trough an exposed succession of sedimentary rocks. The report gives the information about specific locations of Paleocene-Eocene sites for the Badger Explorer field trip aiming at performing the basis for identification of the most optimal site for carrying out the on shore drilling test.

Furthermore the report includes field guide notes and maps, which are relevant for the field trip taking place in the middle of June 2007.

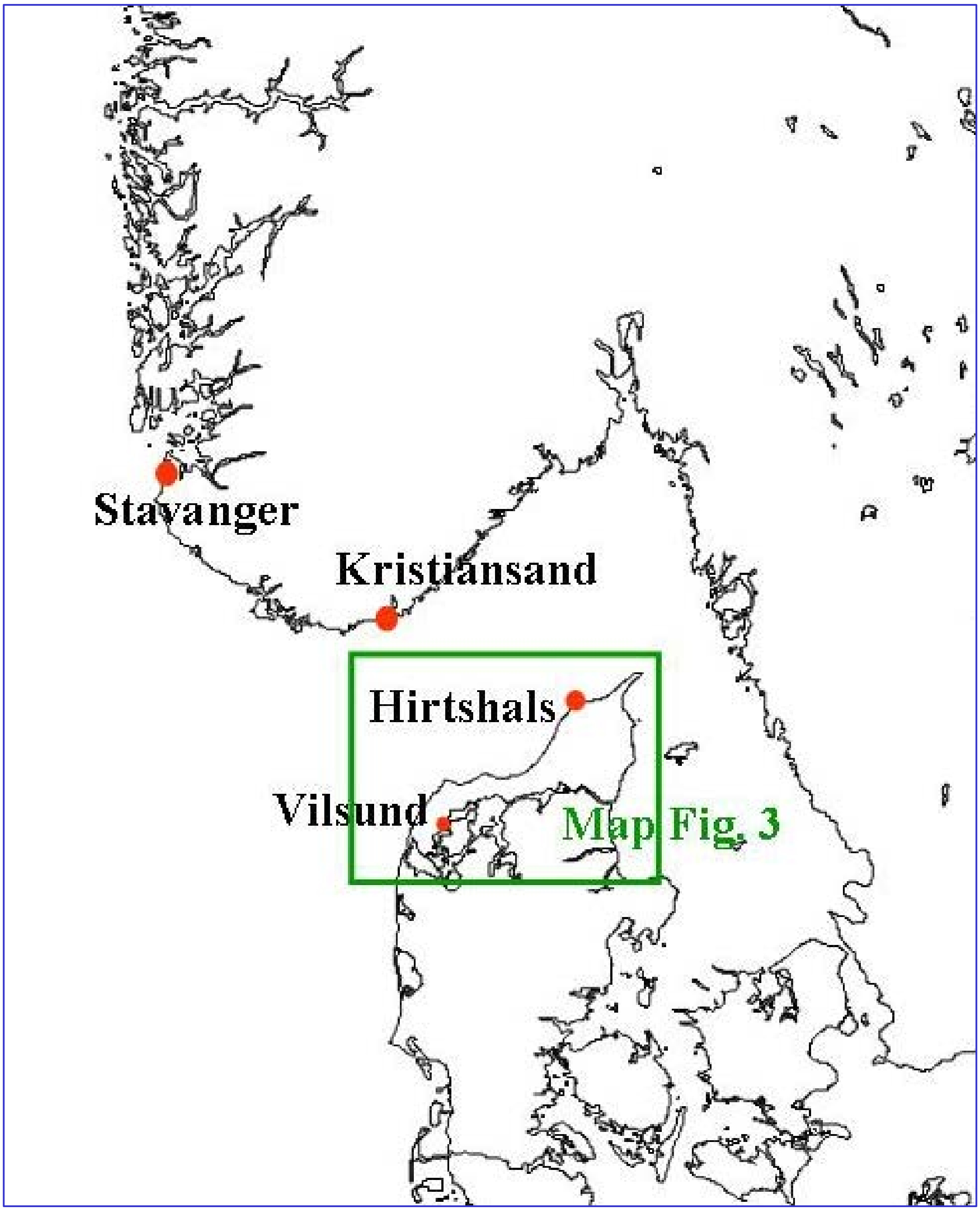

Figure 2. *Location map of Denmark and a few relevant towns essential for the logistics of the test drill project. For more detailed geographic information about northern part of Jutland the map in Fig. 3 should be consulted, the location of which is framed in green.*

The Geological Setting of northern Denmark

The northern part of Denmark is lowland with hills less than 100 m high. One of the frequently used harbours for the entrance to Denmark from Sørlandet in Norway is Hirtshals, which is situated on the north westernmost shoulder of Jutland (Figs 2 & 3). North of Hirtshals the Skagen Odder build out one of the greatest spit system in the world. The spit system (odde) started to form only about 6.000 years ago and is closely related to the main uplift of the land south of Hirtshals. This landscape is known as Vendsyssel, 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 and Fur (Fig. 3), which are to important targets 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.

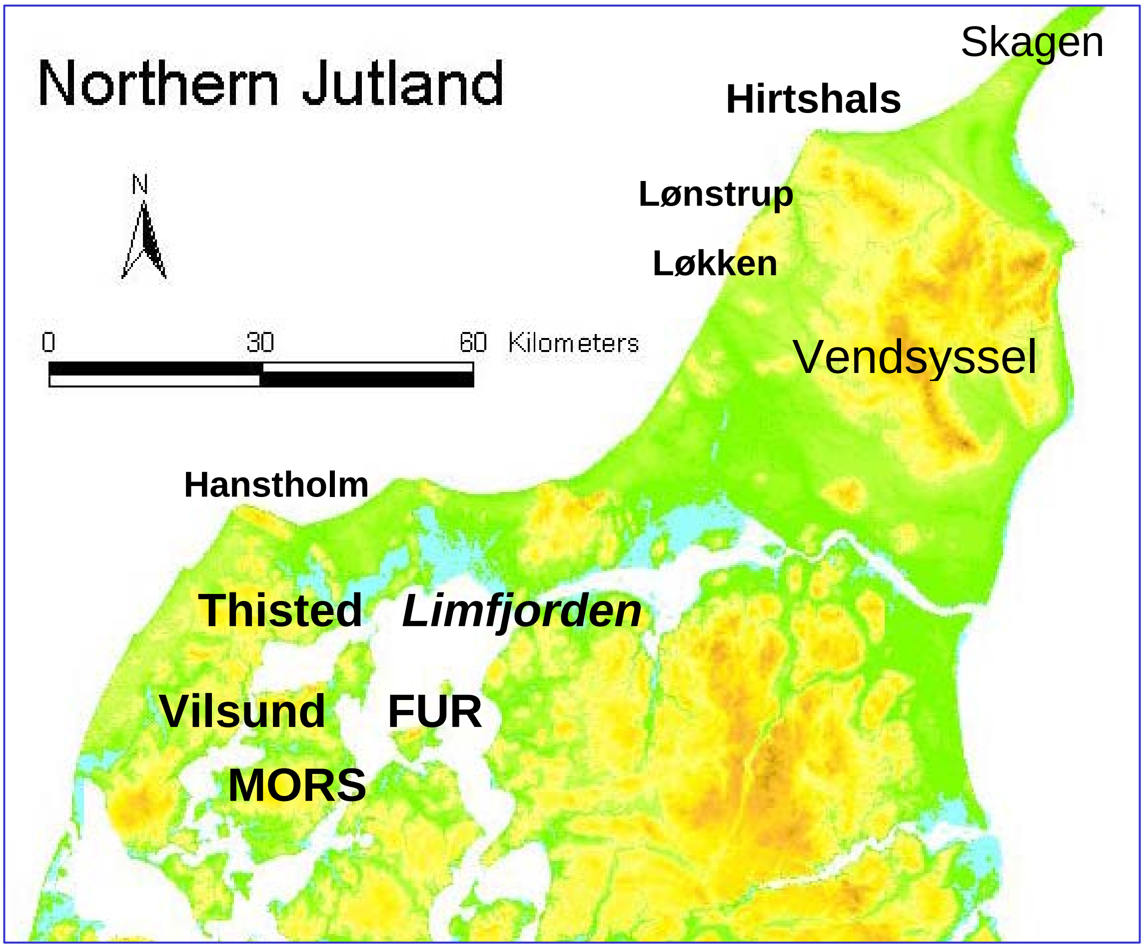

Figure 3. *Topographic map of northern part of Denmark.*

The Pre-Quaternary Geology of northern Denmark

The geological map of the Danish underground is shown in Fig. 4. 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 earth quacks in southern Scandinavia are still concentrated along this zone.

In the basin the sedimentation was initiated during the uplift of the Caledonian Mountain Range. The foreland of this mountain range extended from the Oslo Region and southwards towards the Danish depression. However, sediments from this period (ca. 400 mill. years ago) are not very well know in the subsurface of northern Denmark.

In the Permian period (ca. 270 mill. years ago) strong volcanic activity affected the Oslo Region during the tectonic activity that crated 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 dessert dominated Triassic period in a succession about 3–4 km thick.

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 the build up of 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 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 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. 4). 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 underground in northern Denmark on Fig. 6. 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. Note that 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.

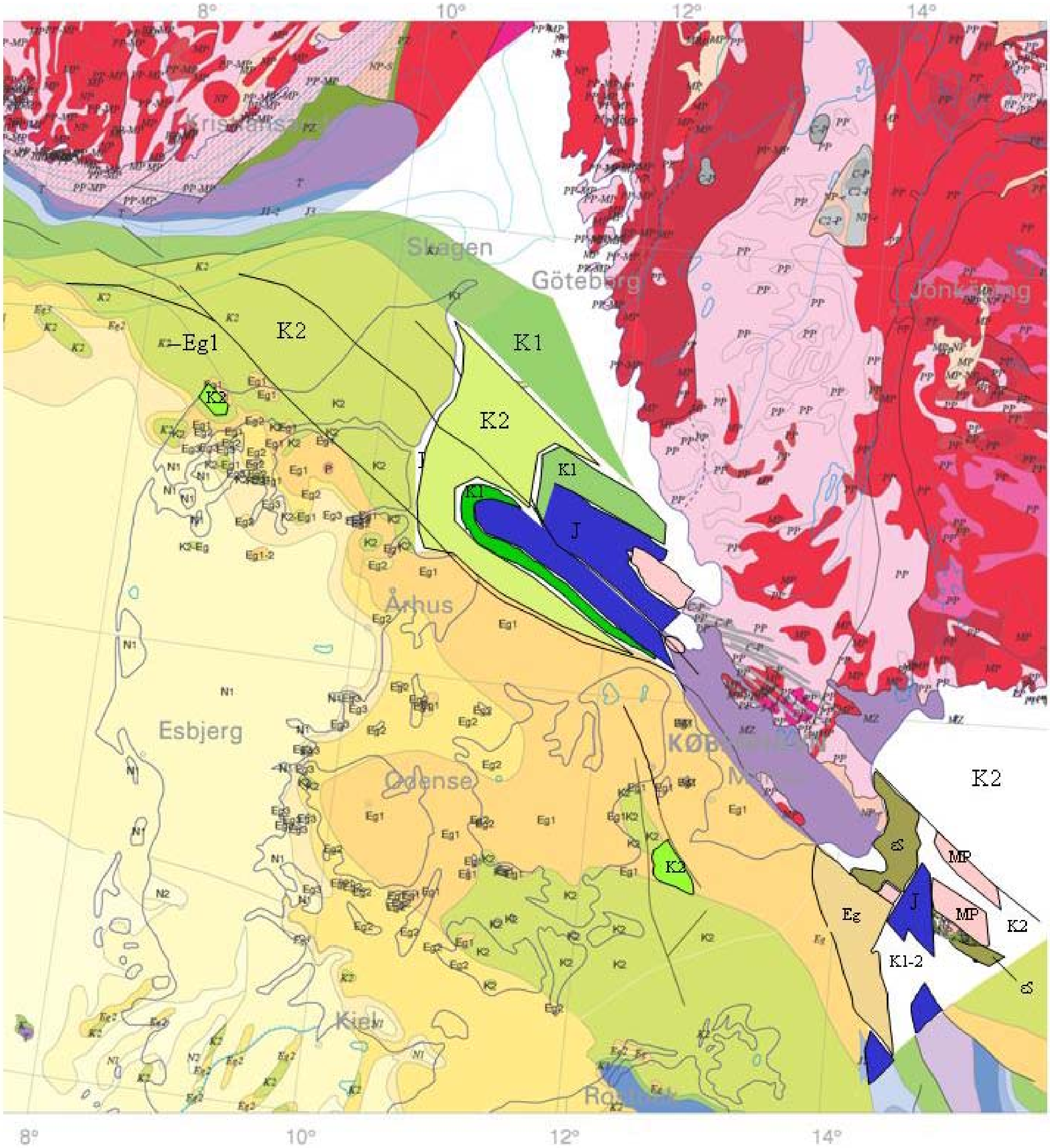

Figure 4. *Pre-Quaternary map of Denmark. Red colours are Precambrian basement rocks at the margin of the Danish Basin. Blue colours are Jurassic and Triassic units mainly occurring in fault blocks in the NW-SE striking Tornquist Fault Zone. Green colours are Cretaceous chalk (K2), yellow-brown colour (EG1) is lower Tertiary limestone and marly clay. The light beige colour (N1) is Miocene sand deposits, which 15 mill. 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. Modified from Pedersen, S.A.S., Gravesen, P. & Vejbæk, O.V. contribution to Sigmond, E.M.O. (2002): Geological map, Land and Sea Areas of Northern Europe, Scale 1:4 mill. Geol. Survey Norway.*

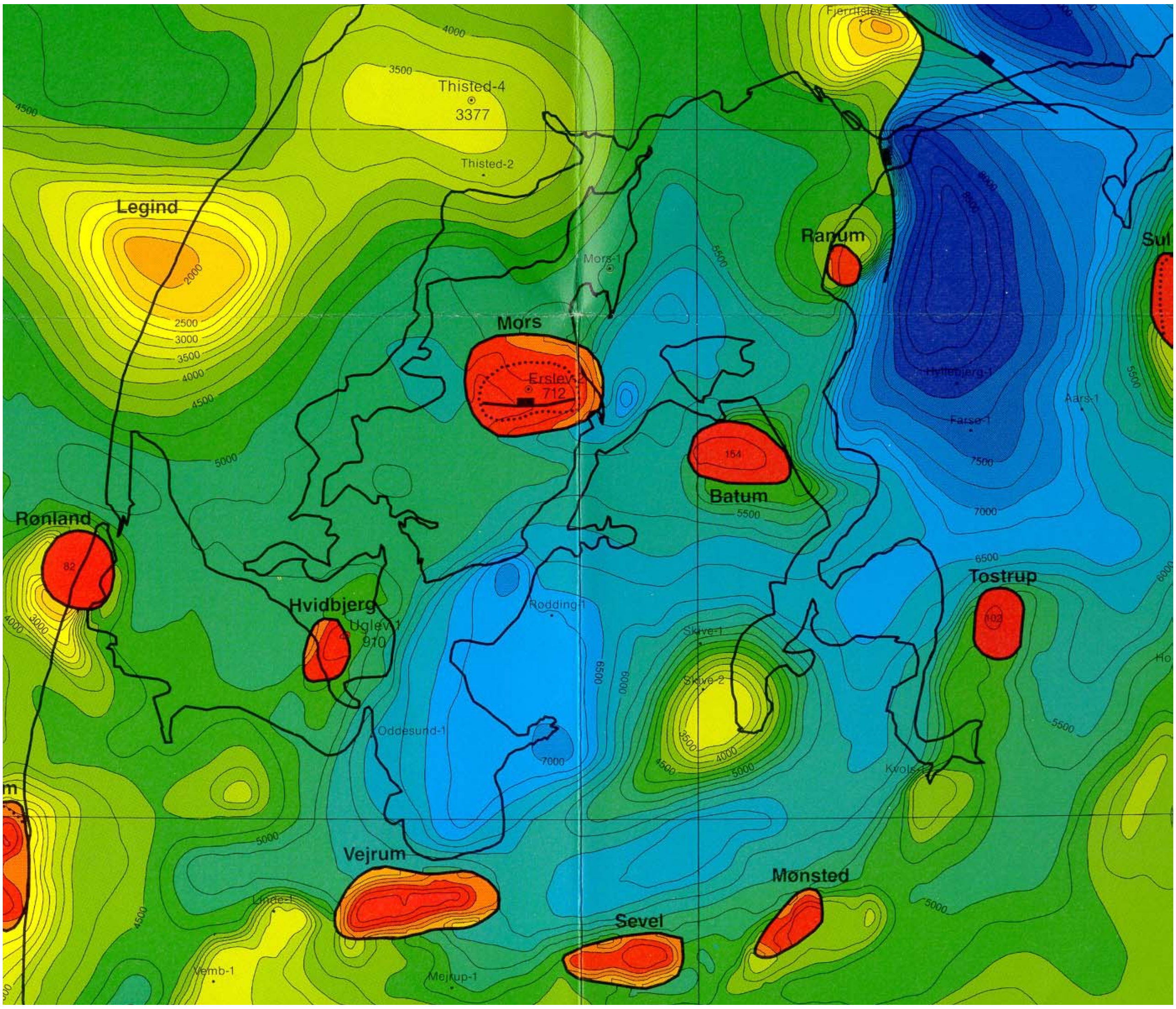

Figure 5. *Location of the salt diapirs (red areas) in the salt diapir province of Western Limfjorden Region. The contours show the depth to the Zechstein salt, which was deposited in the upper part of the Permian period. Thus it can be seen that in the Batum diapir, the salt is only 154 m below ground level, whereas the main salt layer, from where the salt diapir rises, is situated in 5–6 km depth. From Britze, P. & Japsen, P. (1991): Geological map of Denmark 1:400 000, The Danish Basin, Top Zechstein and the Triassic, Geological Survey of Denmark, Map Series No. 31.*

The early time of the Tertiary period in the North Atlantic region was dominated by the opening of the Atlantic Ocean. This tectonic event started about 55 mill. years ago and was associated with an impressive volcanic activity. Volcanic rocks were deposited in Scotland and in 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 mill. years of the geological history. The volcanic activity had also the effect of spreading a lot of volcanic ash. This ash was deposited as distinct layers in the North Sea where they are well known beds in the Early Tertiary (Palaeogene) Sele and Balder Formations. On land these deposits have been known for more than 100 years, although their origin was first really understood in the beginning of the 1990th. Due to the special oceanic conditions in the Palaeogene a lot of diatomite was deposited in the northern part of the North Sea. The diatomite interbedded with ash layers are described as the Fur Formation in northern Denmark (Pedersen & Surlyk 1983). Diatomite deposits are fine grained layers of dead algal deposited from suspension together with clay. A diatom is an algal with a silicate skeleton, which is typically blooming in tropical or subtropical seas dominated by up welling of deep ocean nutrient rich water. Diatomite deposits are also well known from volcanic lake environments, as for example Mywatten on Iceland. Here as well as in other parts of the world the diatomite deposits are used as insulation material. In the northern part of Denmark the clayey diatomite has been excavated for more than 100 years and traded under the name moler (mo-clay). At present a production of absorbing granulate (“cat litter”) is the most successful application of the excavated material.

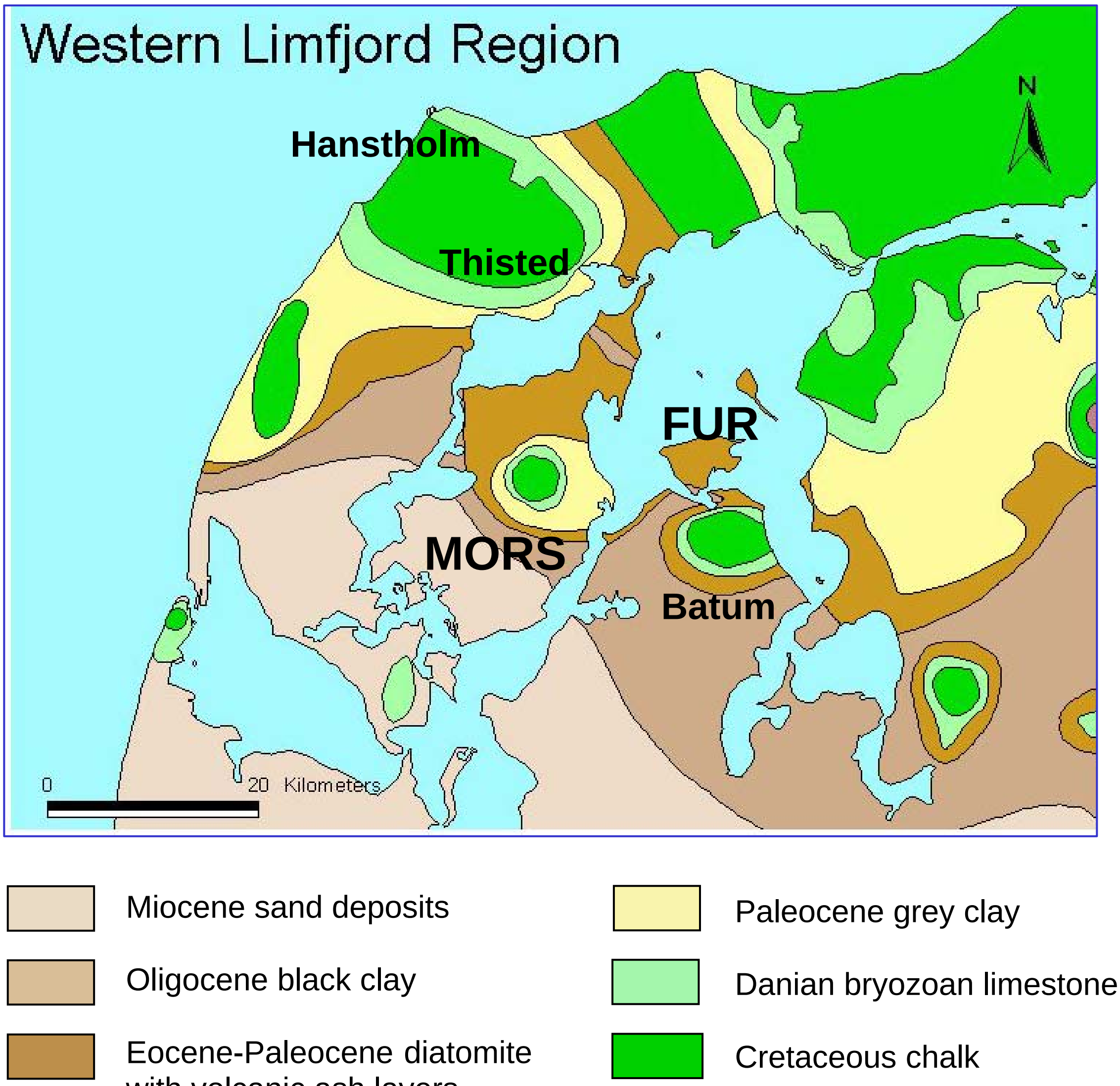

Figure 6. *Geological map of the Pre-Quaternary surface in the western Limfjord Region. The map is also named “the underground map” because it shows the geology on the surface from where the glacial cover deposits have been removed. In general these cover deposits have a thickness from a few to 30 m. Simplified from Håkansson, E. & Pedersen, S.A.S. (1992): Geologisk Kort over den Danske Undergrund. Varv.*

The Quaternary of northern Denmark

The surface geology in the Western Limfjorden Region is dominated by glacial deposits (Fig. 7). During the peak of the last glaciation the region 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. 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.

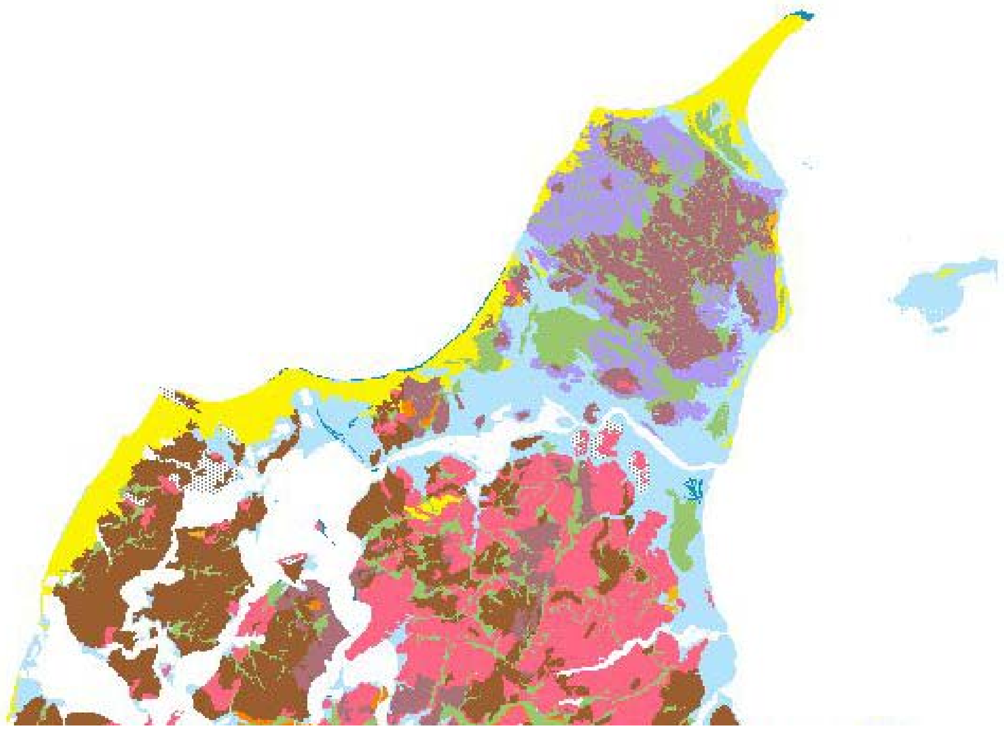

Figure 7. *Geological map of the Quaternary deposits in northern Jutland. Brown colours are till deposits, mainly deposited as lodgement till by the Norwegian and Swedish Ice Streams 30 000–20 000 years ago. Red colour is melt water sand and gravel deposited on the outwash plane in front of the advancing ice streams. 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 represent the aeolian dune sand deposited along the Westcoast. From Pedersen, S.A.S. (1989): Danmarks Jordarter, målestok 1:200 000. Danmarks Geologiske Undersøgelse.*

Glaciotectonics

The most characteristic landscape elements in the Western Limfjorden Region are the glaciotectonic complexes. A glaciotectonic complex is a substratum of sediments and sedimentary rocks deformed by the compression related to an advancing gletscher. The generated structures are characterised by similarity in style and architecture, and the complex is a structural identity with definite boundaries in space and time. The glaciotectonic complex creates a landscape of parallel ridges perpendicular to the ice push direction (Fig. 8).

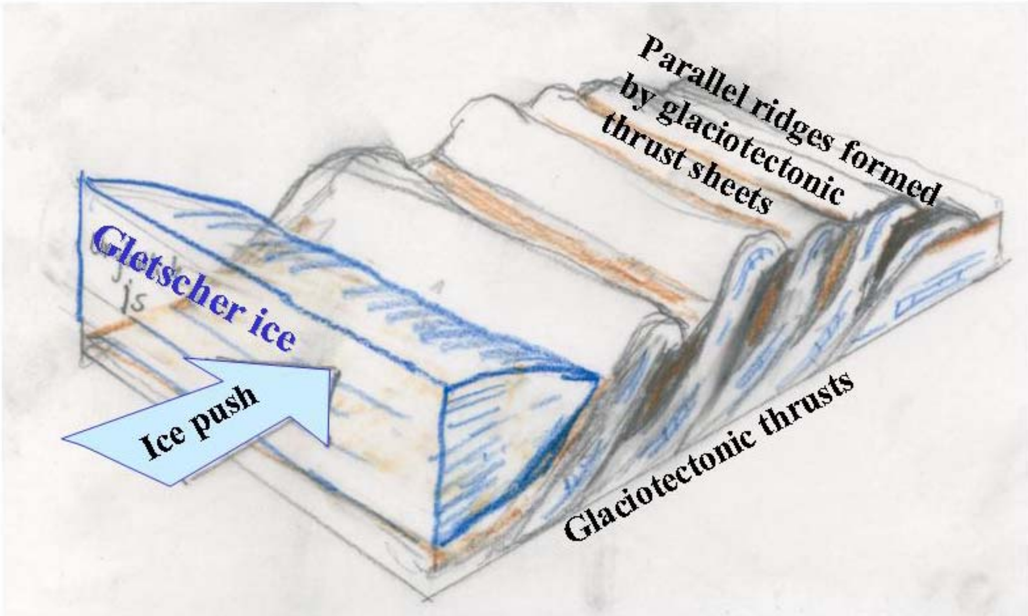

Figure 8. *Principle sketch of a glaciotectonic complex. The glaciotectonic thrust faulting creates a landscape with parallel ridges perpendicular to the direction of the ice push. The thickness of the thrust sheets are in the order of 50 m, the crests are elevated up to 100 m above the primary depositional position of the layers. Along strike the length of the crests can be up to 10 km.*

All the pits in the mo-clay area operate in glaciotectonic complexes. In a succession of Eocene diatomite with ash layers, which had been thrust up in an anticline, the excavation of the diatomite is started in the centre of the anticline and successively a long trench is mined along the strike of the thrust sheet.

Along the coasts of Limfjorden a number of cross sections through the glaciotectonic complexes are exposed. Here instructive information on the internal framework of the landscape can be studied directly. The concept of glaciotectonics forms the basis for understanding why and how the Tertiary formations crop out in the landscape 60 m above sea level.

Locations for potential test-drill sites.

Two main areas will be presented as candidates for test-drilling sites. The first area is the northern part of the island of Mors and the second area is the island of Fur (Fig. 3). On both islands mo-clay exploitation takes place in the glaciotectonic complexes with deformed Palaeogene sedimentary rocks. Furthermore a small number of coastal exposures will be visited for the demonstration of stratigraphy, and a chalk pit at the top of the Batum Salt Diapir will be briefly visited (Fig. 5).

Locations on Mors

On Mors four locations will be demonstrated: 1) Ejerslev mo-clay pit, 2) Skarrehage mo-clay pits, 3) Feggeklit with folded ash layers, and 4) Hanklit thrust sheet along a coastal profile (Fig. 9).

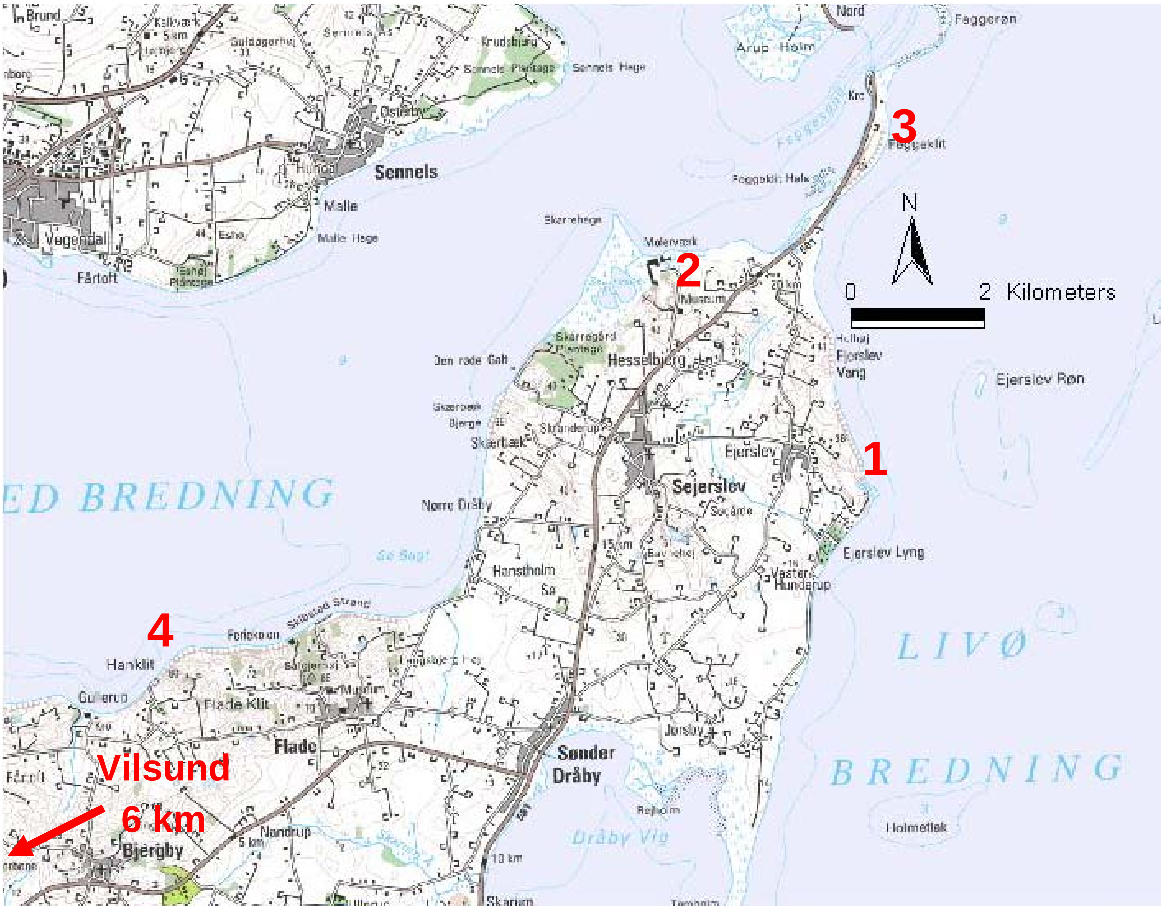

Figure 9. *Locality map of northern Mors. 1) Ejerslev mo-clay pit with exceptional well exposed anticline in 30 m deep pit. 2) Skarrehage mo-clay pits, 20 m thick successions in a deeper stratigraphic level. 3) Feggeklit with nicely folded ash layers in diatomite along a coastal cliff. 4) Hanklit with 200 m long and 60 m thick thrust sheet displaced to the south by the Norwegian Ice Stream.*

Ejerslev mo-clay pit

Ejerslev mo-clay pit is situated at the east coast of northern Mors, location 1 on Fig. 9.

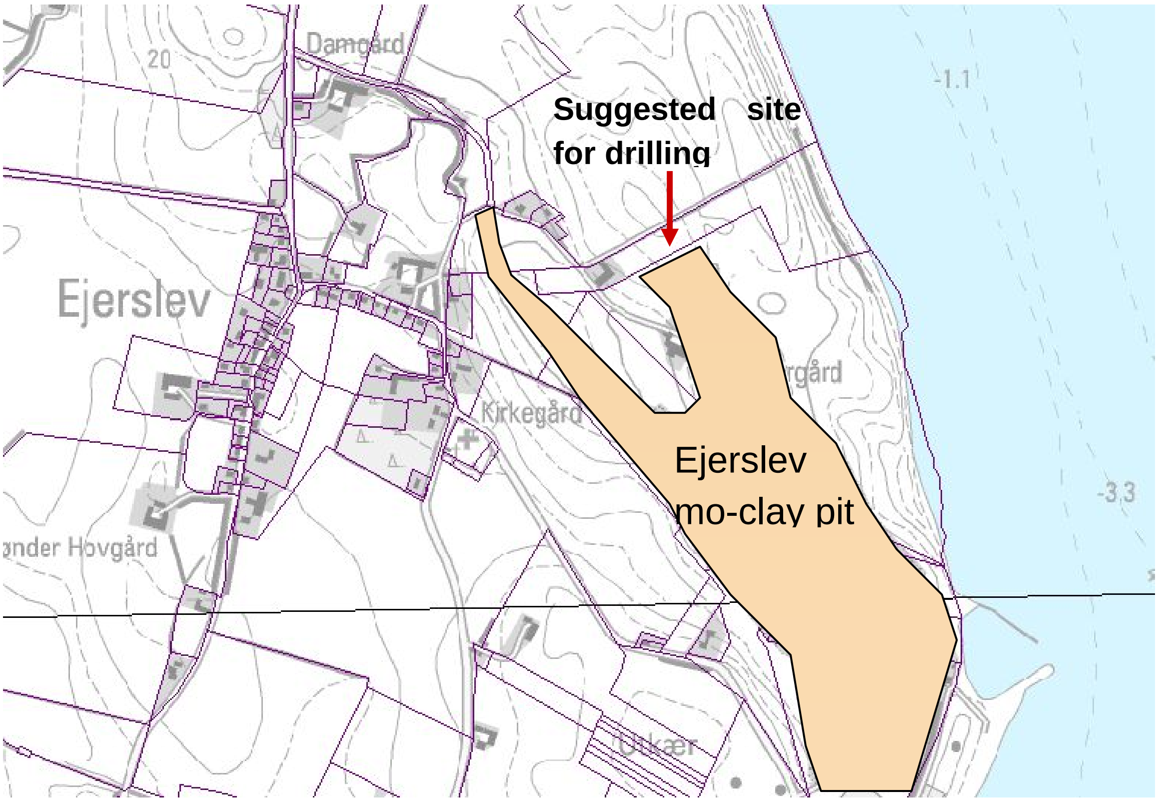

Figure 10. *Detailed map of the Ejerslev mo-clay pit. One suggested location for drilling is shown, but alternative possibilities exist in the pit as well as along the margins.*

Figure 11. *The northern wall in the Ejerslev pit is suggested for test-drilling site. The red arrow corresponds to the location of red arrow in Fig. 10.*

Skarrehage mo-clay pits

The Skarrehage mo-clay pits are situated in the vicinity of the Skarrehage mo-clay granulate factory (locality 2 in Fig. 9) on the western side of northern Mors. At the pits a local museum is situated, which instructively tells about the geology of the mo-clay and the numerous fossils found in the diatomite between the ash layers.

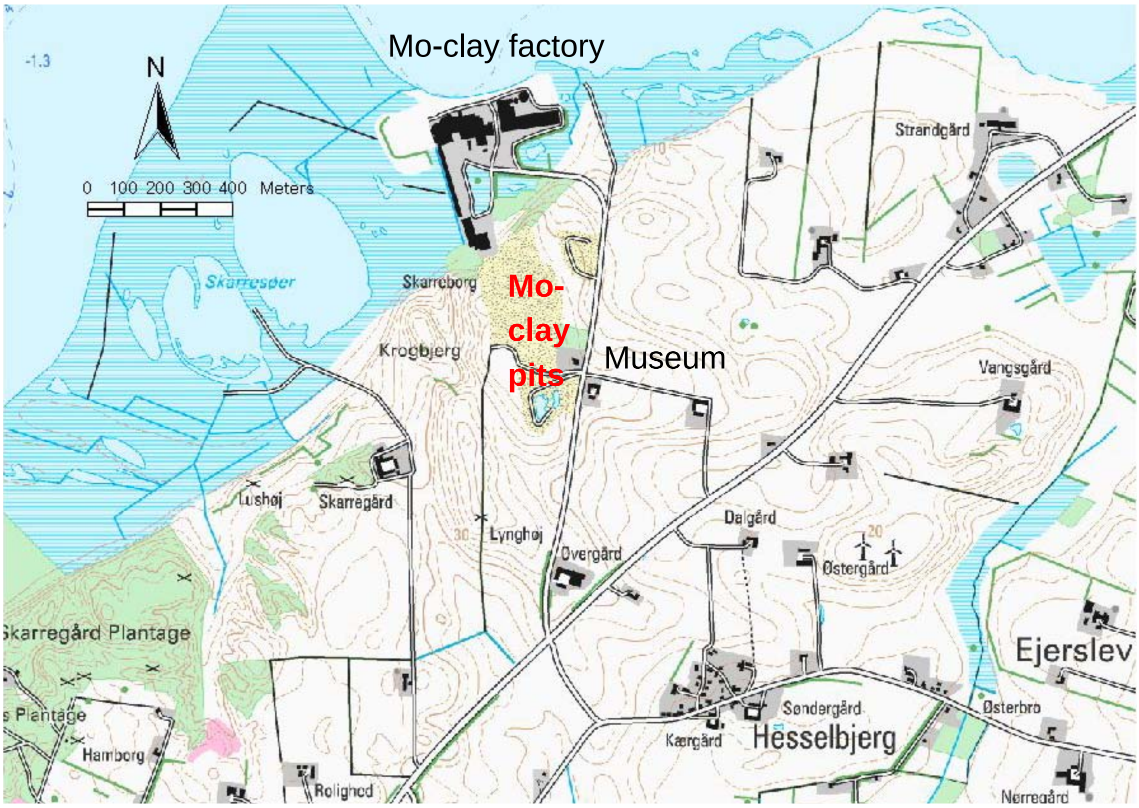

Figure 12. *Detailed map of the Skarrehage area. Two of the suggested sites for drilling are at the wall of the southern Skarrehage pit (Fig. 13), and in the central pit just opposite the Museum, shown on the picture in Fig. 14.*

Figure 13. *The syncline structure in the southern Skarrehage pit.*

Figure 14. *The dipping strata of the Palaeogene Fur Formation in the eastern side of the central pit in the Skarrehage area.*

Feggeklit

The Feggeklit cross-section is one of the most instructive cross-sections across a folded glaciotectonic complex. The cross-section is exposed on the east side of the northernmost peninsula of Mors (locality 3 in Fig. 9). The cliff is about 800 m long, and it is recommended to pass the cliff by parking at the field to the south and then work along the profile, if the water and weather conditions permit it.

Along the cross-section the upper part of the Fur Formations is represented. The ash layers recognisable in the diatomite are ash layer no. +19 to ash layer +118. Above the Fur Formation three tills and a glaciolacustrine succession are present. The lower till is a Saalian unit deposited during the former glaciation about 300 000 years ago. The next till is deposited by the Norwegian Ice Stream, and the varvig beds of the glaciolacustrine unit have been dated to 21 000 years ago. The till above these beds is deposited by the Sweedish Ice Stream, which was also responsible for the glaciotectonic deformation of the deposits as illustrated in the model shown in Fig. 15. The deformation is interpreted as a proglacial deformation created by the gravity spreading of the ice cap advancing from the northeast towards the foreland to the south. The measured profile across the structures is shown in Fig. 16. According the calculation carried out with the aid of balanced cross-section the décollement zone for the thrust fault deformation is situated about 100 m below sea level, which corresponds to the position of slippery bentonitic clay in the lower part of the Palaeogene.

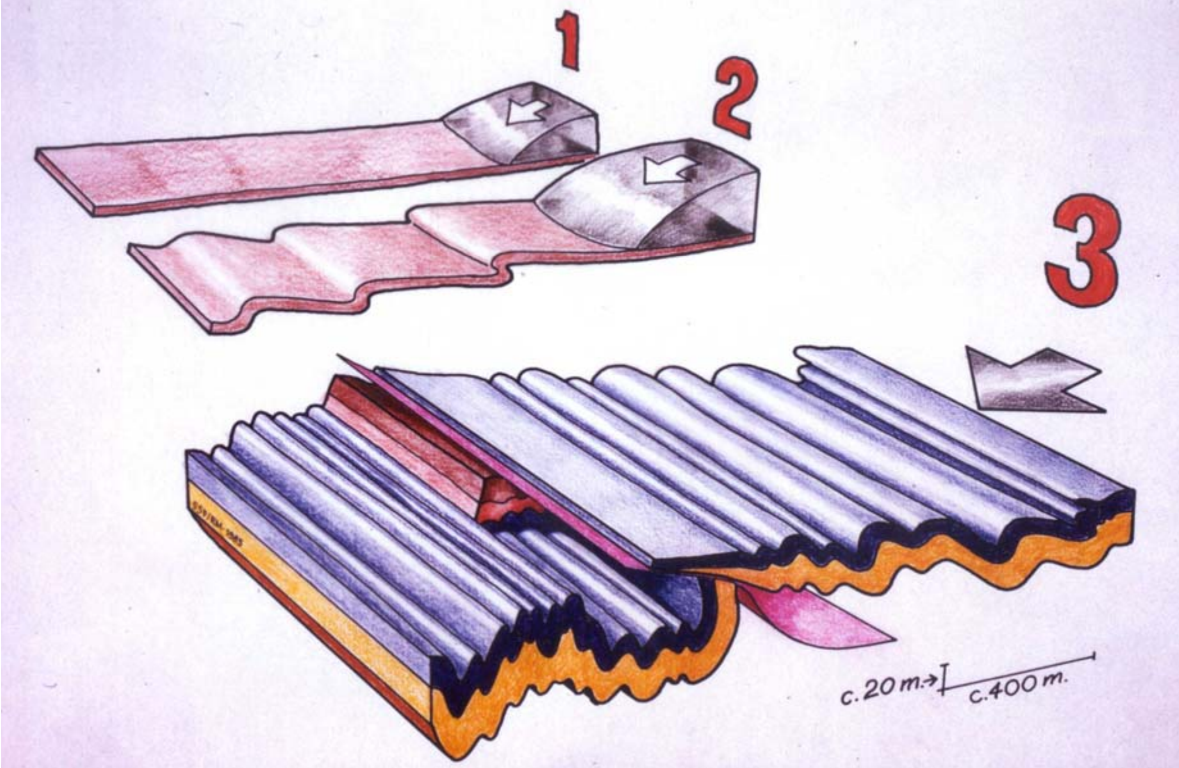

Figure 15. *Dynamic model of the deformation of the Feggeklit fold complex.*

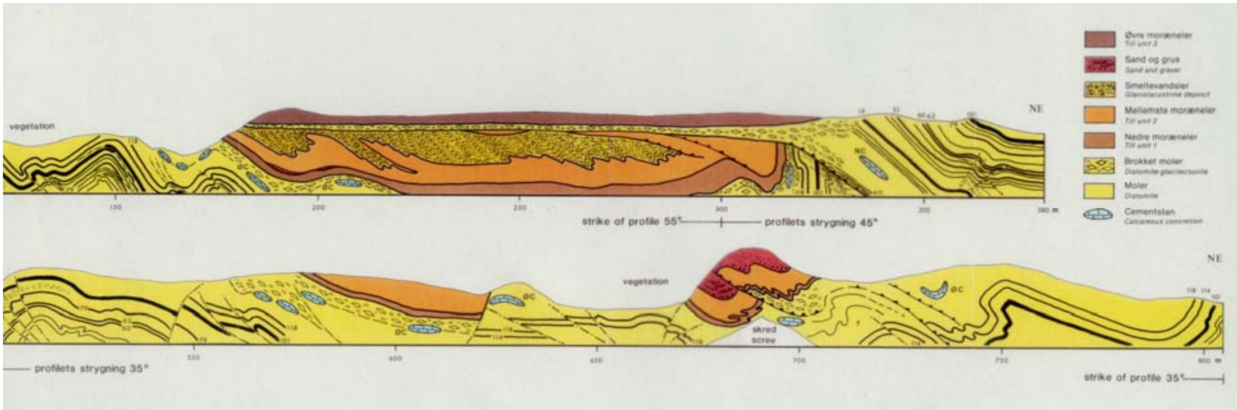

Figure 16. *The Feggeklit cross-section. Note the thrust fault in the right side of the upper diagram, this thrust fault has been calculated to be rooted in a décollement zone ca. 100 m below sea level. From Pedersen, S.A.S. (1996): Progressive glaciotectonic deformation in Weichselian and Palaeogene deposits at Feggeklit, northern Denmark. Bull. Geol. Soc. Denmark 42, 153-174.*

Hanklit

Hanklit (loc. 4 in Fig. 9) is one of the most impressive cross-section through at 60 m thick thrust sheet, which was displaced more than 200 m up over the foreland to the south due to the push from the Norwegian Ice Stream advancing from the north about 28 000 years ago.

Figure 17. *The Hanklit thrust fault sheet. The thick black marker bed in the central part of the thrust sheet is ash layer +101 and the rusty calcareous concretion surrounding it. The top of the sheet comprises a 15 m thick gravel dominated glaciofluvial unit.*

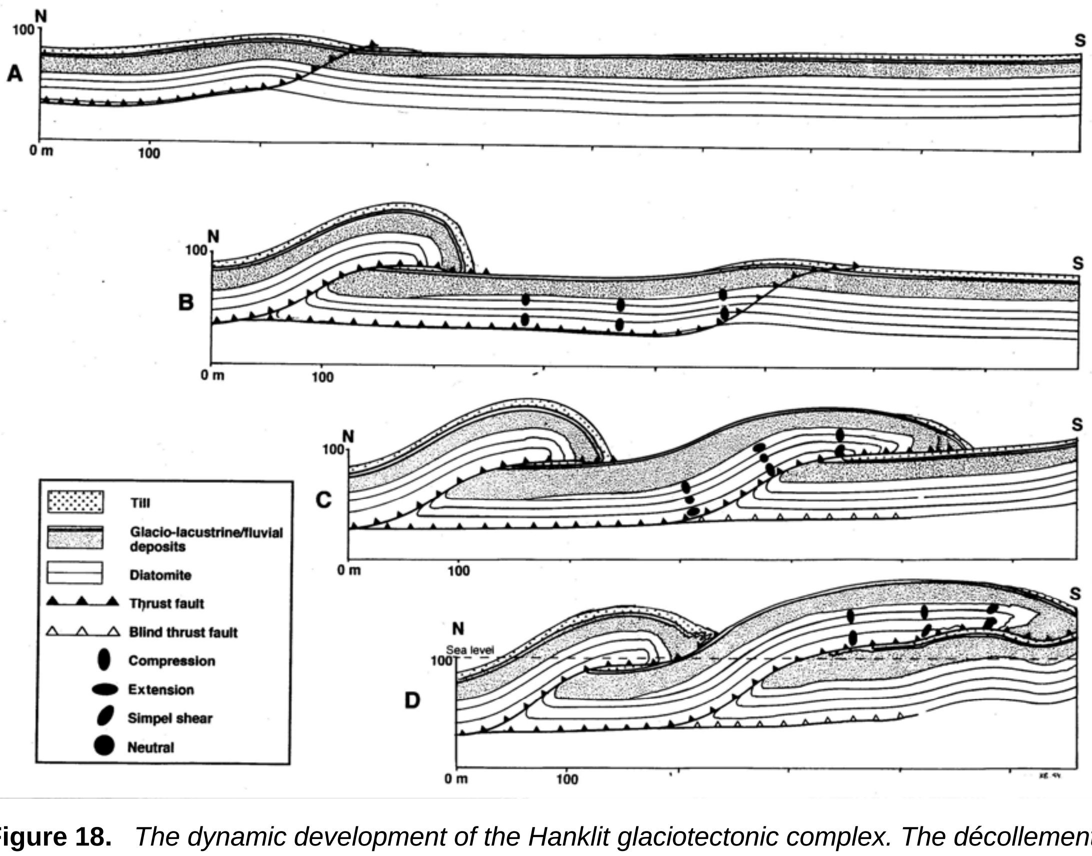

Figure 18. *The dynamic development of the Hanklit glaciotectonic complex. The décollement surface is situated about 80–100 m below sea level. The top of the Fur Formation was situated 15–20 m below sea level prior to deformation, which resulted in an elevation op to the 60 m above sea level. The thrust elevation of the Fur Formation created the elongated hill landscape of the northern Mors. From Klint, K.E.S. & Pedersen, S.A.S. 1995: The Hanklit glaciotectonic thrust fault complex, Mors, Denmark. Danmarks Geologiske Undersøgelse, Ser. A, nr. 35, 30 pp.*

Locations on Fur

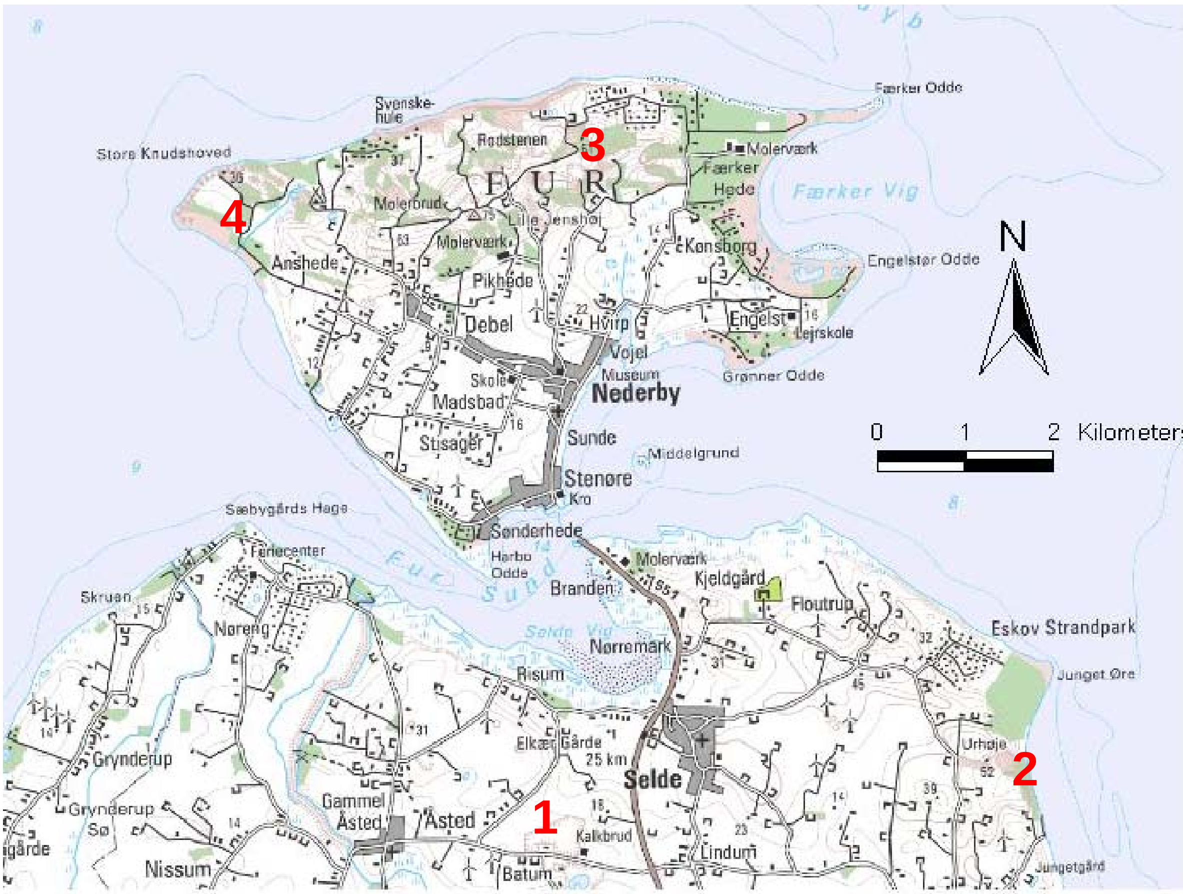

Figure 19. *Localities to be visited on the way to Fur and at the top of the hilly area on Fur. 1) Batum chalk pit, 2) the abundant Junget mo-clay pit, 3)The hill ridge on the northern part of Fur, 4) The Fur Brewery and the Knude Klint cross-section.*

The island of Fur is situated north of the peninsula of Salling about an hours drive from Vilsund. On the way we will cross the bridge of Salling Sund, and the strait between Salling and Fur is crossed with a ferry. The first locality, which is only a brief stop, is the chalk pit on top of the Batum Salt Diapir (Fig. 20). The chalk pit might be interesting for a test-drilling, if experiences are needed for drilling through the 500–800 m thick Chalk Group in the Norwegian-Danish Basin.

On the north-eastern flank of the salt diapir the Junget glaciotectonic complex is situated (loc. 2 in Fig. 19). The Junget glaciotectonic complex is thrust from the northeast towards the southwest up along the north side of the salt diapir structure. The imbricate structures dominating this thrust complex is illustrated in Fig. 21. In the southernmost part of the Junget glaciotectonic complex an abundant mo-clay pit is situated. This field may serve as an alternative drill site if the demand is a horizontal succession to be penetrated.

On Fur the pits situated in the hill crest on the northern part of the island will be demonstrated. If time permits a walk to the western most point on will conclude the day’s trips.

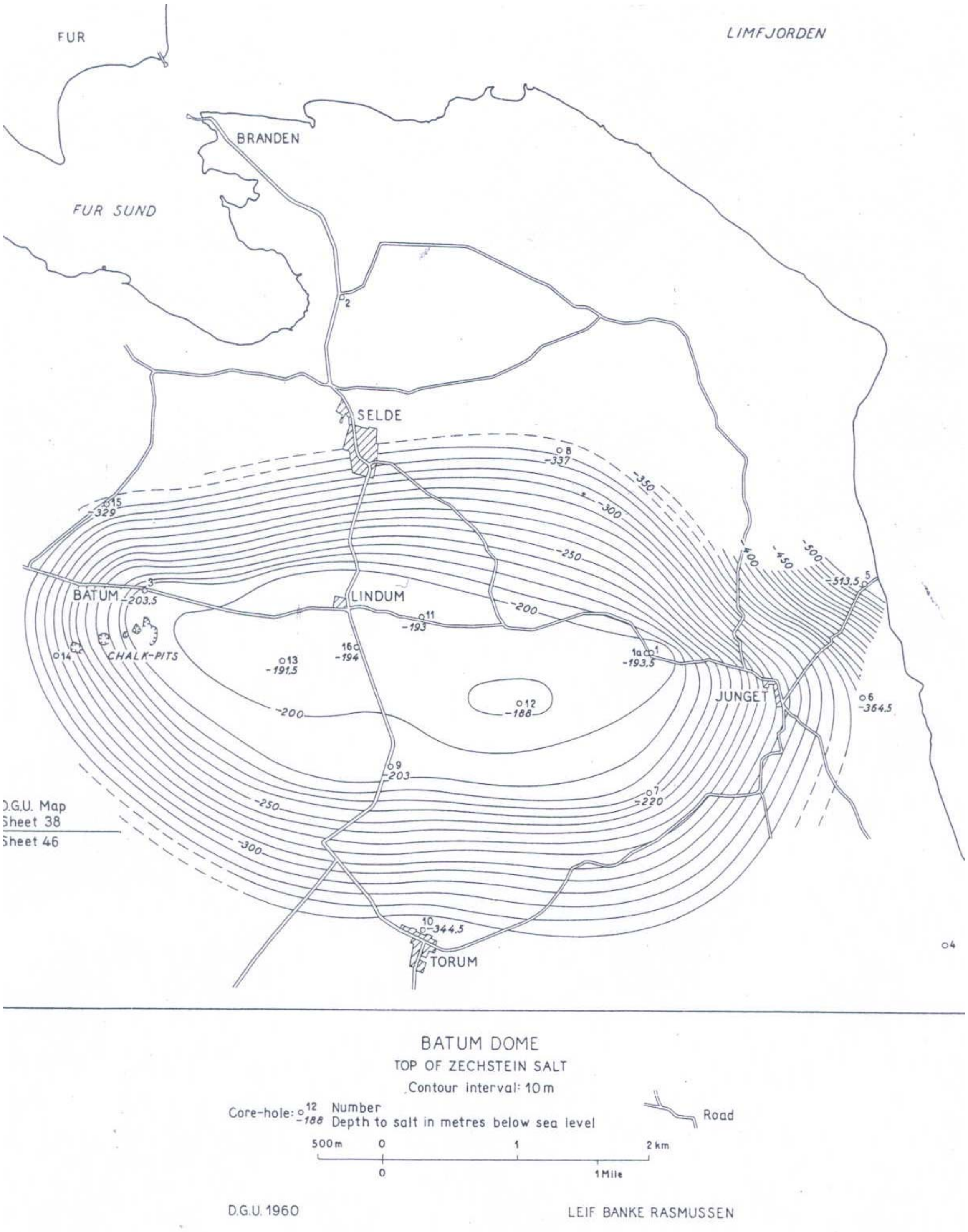

Figure 20. *Contour outlining the top of the Batum Salt Dome. From Rasmussen, L.B. (1960): Geology of North-Eastern Jylland, Denmark. Sorgenfrei, T. (ed.): International Geological Congress 21, Norden 1960, Guide to Excursion Nos 42 and C 37, Part 2, 37 pp.*

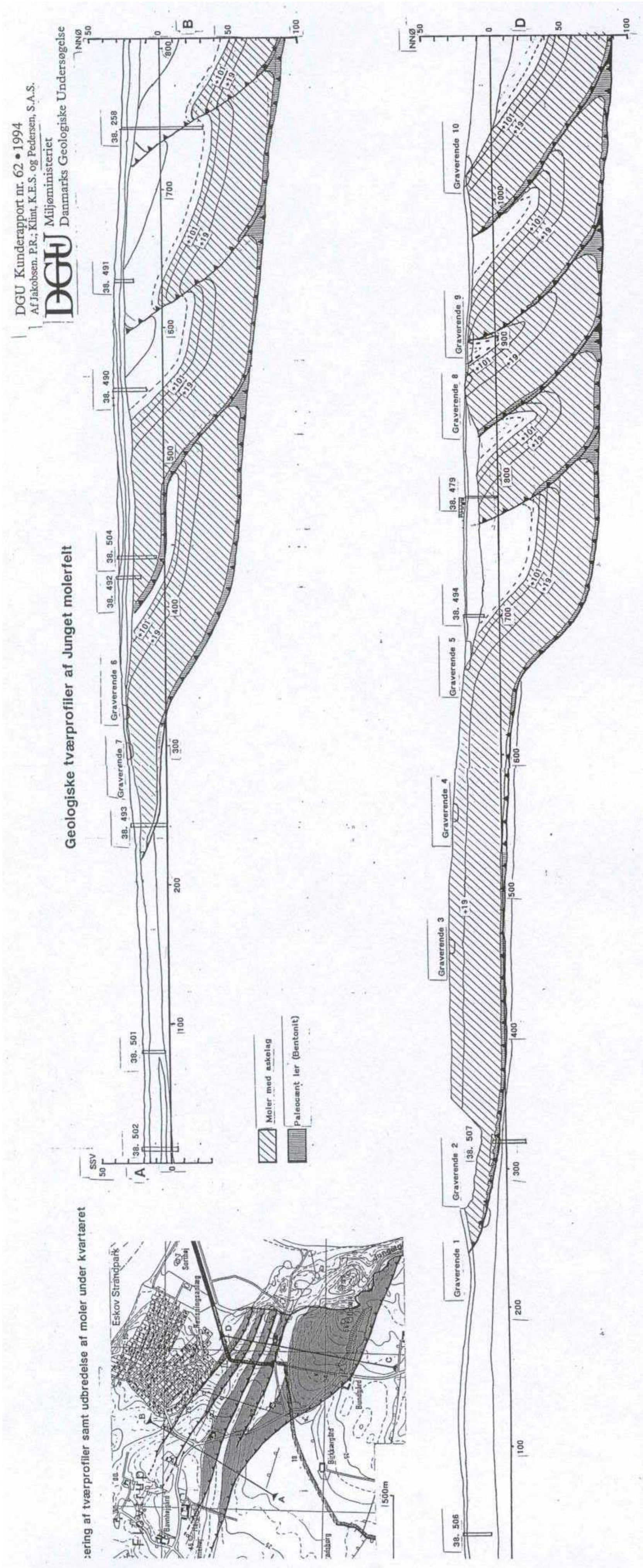

Figure 21. *Two cross-sections of the thrust fault complex at Junget, on the north-eastern flank of the Batum Salt Dome. Note that the Junget mo-clay pit is situated in the left end (to the south) of the cross-section in the lower diagram. The position of the cross-sections are given on the map in the left corner.*

From Jakobsen, P.R., Klint, K.E.S. & Pedersen, S.A.S. (1994): Lerundersøgelse i Junget Molerfelt. DGU Kunderapport nr. 62, 1994.

The hill crest of Fur

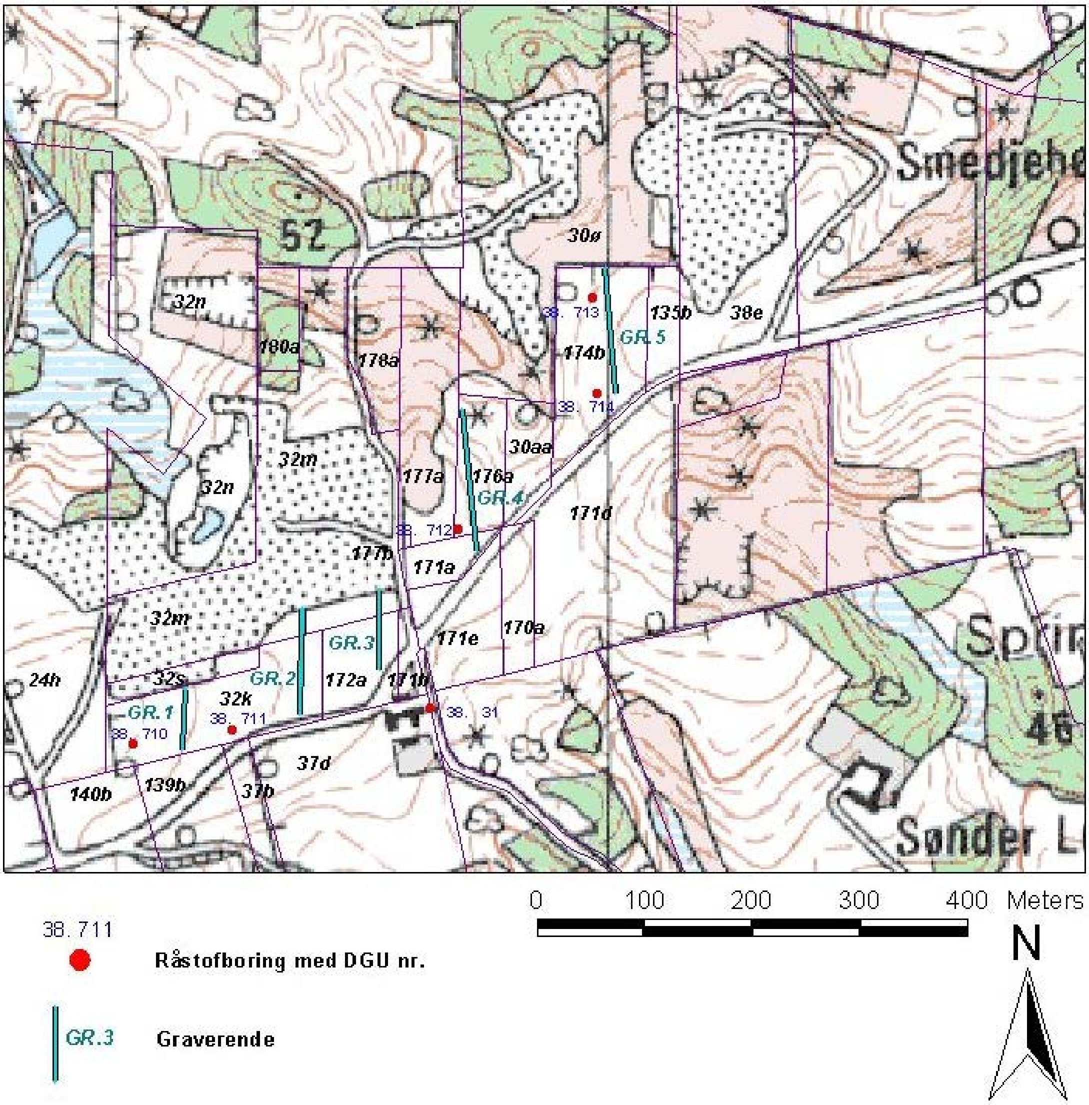

Figure 22. *Map of the mo-clay pits to be visited in the hill crest of Fur.*

The exact position of a test site in the vicinity of the pits in the hill crest on Fur (Fig. 22) can not be envisaged, because the excavation of the pits is very active and it is difficult to predict, where an attractive site could be. However, we will take at tour along the hill crest and look at the possibilities. The crest it self constitute the central part of the glaciotectonic complex of Fur. A cross-section of the complex can be seen in Fur Knudeklint, which is situated in the north-westernmost corner of the island. The pit suggested for a drill site is presented in Figs. 23 and 24 demonstrate a cross-section of the structural geology in the crest.

Figure 23. *Photo of cross-section in the eastern wall of one of the mo-clay pits in the central part of the hill crest in the northern part of Fur. The ross-section through the southwards verging fold and thrust structures were deformed by the Norwegian Ice Stream about 24 000 years ago.*

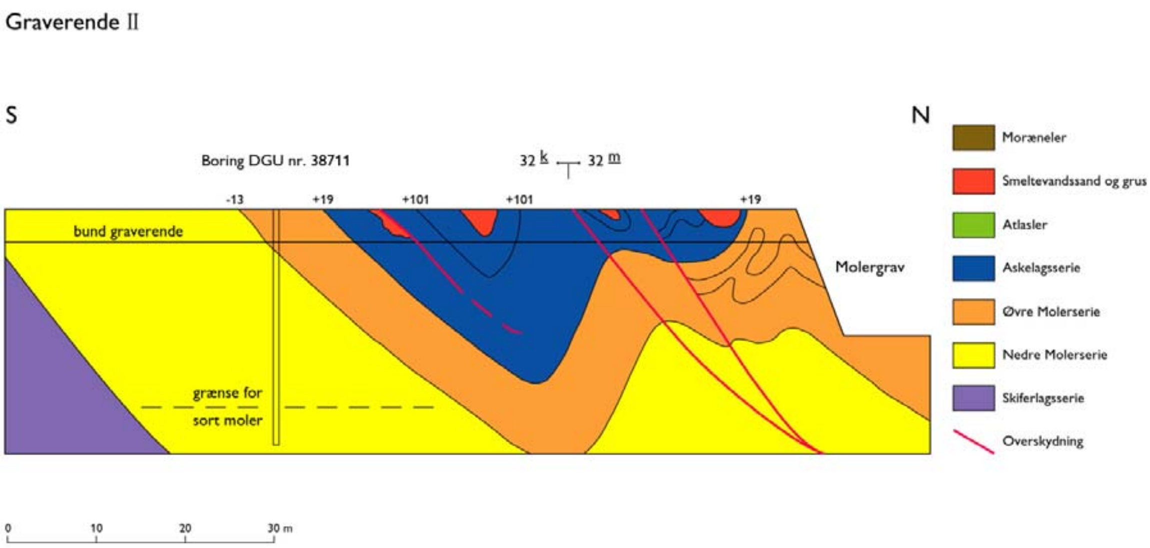

Figure 24. *In the schematic diagram below the structural framework has been constructed on the basis of the well DGU 38 711 and a 3-4 m deep trench excavated in the top of the cross-section. Pedersen, S.A.S.(2002): Strukturgeologisk undersøgelse af molerforekomsten i den centrale del af bakkekronen på Fur. GEUS rapport 2002/93.*

The glaciotectonic complex on Fur has some of the same qualities as the complexes on Mors and at Junget. But as it is not easy to judge exactly, which one will be the best in relation of the present position of excavation and agricultural planning, they are here presented.

Program for excursion

The excursion for testing drill-sites starts Sunday evening 17th of June 2007 at Vilsund Færge-kro with a presentation of the local conditions and relations to be addressed on. The following two days we will drive around in the landscape of the Western Limfjorden Region and look at the actual sites to judge the possibilities. First day will be concentrated on Mors, and the next day the island of Fur will be on the agenda. The excursion ends Wednesday in the morning at Vilsund Færgekro, where we will have a summary and evaluation meeting at breakfast.

1. 17.06.2007: 21.00 Arrival at Vilsund Færgekro
2. 17.06.2007: 22.30 Sunday evening: powerpoint presentation by Stig Schack Pedersen, GEUS (may be postponed to Monday morning).
3. 18.06.2007: Breakfast Monday morning at 07.30. Departure from Vilsund at 08.30 (or 09.30 depending on the decisions).
4. 18.06.2007: Drive form Vilsund to Ejerslev (lok. 1 on Mors). During the tour across landscape we will drive along one of the most impressive glaciotectonic complexes in the world with parallel elongated hills, and we will visit the peak of the island 89 m a.s.l. named Salgjerhøj.
5. 18.06.2007: Visit in the Ejerslev mo-clay pit. If it is a rainy day boots are strongly recommended. The walls of the pits are very freshly excavated and may be very photogenic. It is the recommended site for drill operations, but we will investigate it.
6. 18.06.2007: Just before lunch time we will walk the Feggeklit profile, loc. 3 on Mors.
7. 18.06.2007: The lunch break will be at the Mo-clay Museum at Skarrehage. If time permits we will go and see the museum, which exhibits beautiful fossils of fish, birds, plants and insects 50 mill. years old.
8. 18.06.2007: The Skarrehage mo-clay pits, loc. 2 on Mors. From the Museum we will walk around the pit area and have a look on the facilities. New excavations at active just below the "Yellow House" which might be of interest.
9. 18.06.2007: On the way back to Vilsund we will visit the Hanklit site, loc. 4. on Mors. The Hanklit cliff section is one of the most impressive thrust fault site in the glaciotectonic record. Furthermore it gives an excellent demonstration of the full stratigraphy of the Fur Formation.

10. 18.06.2007: End of day at Vilsund Færgekro.
11. 19.06.2007: Breakfast Tuesday morning at 07.30. Departure form Vilsund at 08.30.
12. 19.06.2007: Drive from Vilsund to Sallingsund Bridge, further on to Batum Salt Diapir (loc. 1 on the Fur trip).
13. 19.06.2007: Demonstration of the Batum Salt Diapir structure.
14. 19.06.2007: Visit to the Junget abundant mo-clay pit, loc. 2 on the Fur trip.
15. 19.06.2007: Drive to the ferry for Fur.
16. 19.06.2007: Visit to the hill crest of Fur, loc. 3. on the Fur trip. Several mo-clay pits will be investigated for their potential of being sites for test-drilling.
17. 19.06.2007: Lunch break at the Fur brewery. Very famous site on Fur and very good ale. The brewery was developed in the factory of the former mo-clay brick production.
18. 19.06.2007: Walk along the beach to the Knude Klint profile. Very scenic cliff section and fossils may be found.
19. 19.06.2007: Drive back to Vilsund. The local centre town Nykøbing may be visited on request. Furthermore the landscape of central Mors may be demonstrated, before we end up in Vilsund for our supper.
20. 20.06.2007: Breakfast Wednesday morning at 07.30. Evaluation meeting 08.15-09.00. Departure from Vilsund at 09.00. The drive to Hirtshals will take about 2 hours.