DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/30**

MapField study area LOOP 2: Establishing a geological event chronology

Peter B. E. Sandersen & Anders Juhl Kallesøe

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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Table of contents

1. Introduction

The LOOP 2 area, situated in the northern part of Denmark (Figure 1 and Figure 3), features a highly complex subsurface architecture, which is evident from the geological and geophysical data (Sandersen & Kallesøe 2021). The area also shows a remarkable topography that matches the complexity of the subsurface and suggests a direct link between the shallow and the deep geology. In MapField, the focus is on the vulnerability of the surface water and the shallow groundwater with a specific focus on nitrate. In the LOOP area, near-surface occurrences of organic rich sediments draw attention because of a potentially high reduction capacity (Kim et al. 2021). The occurrence of former lakes and bogs does not always have a straightforward geological explanation, especially when present on lateglacial outwash plains that normally would be considered as well-drained (Sandersen & Jørgensen 2015). Co-interpretation of the highly detailed tTEM-data and the high-resolution LiDAR terrain data in the LOOP 2 area revealed a geological complexity that appears to be linked to both the Pleistocene glaciations and tectonic events with roots in the deep parts of the subsurface.

To model a complex geology in 3D, it is necessary to bring forward possible explanations of how the subsurface was formed and how the individual parts of the succession are linked in terms of formation. Therefore, a description of the regional geological setting, descriptions of the individual parts of the sedimentary succession and an interpretation of the topography are combined to produce a Geological Event Chronology (GEC). The GEC is a narrative that sketches the probable chain of events that could lead to the character and architecture of the subsurface as we see it today. The purpose of the GEC is to function as a basis for the 3D geological modelling, because it conveys an explanation of what formed the subsurface and it creates a relation between the individual parts of the subsurface in both 'time and space'.

The purpose of this report is to describe the workflow and the interpretations that have led to establishing a GEC in the MapField LOOP 2 area in northern Jutland, Denmark. The work presented in this report is based on the geological mapping published in Sandersen & Kallesøe (2021).

In this report we place the LOOP 2 area in a regional geological context, describe the sedimentary succession and analyse the topography in more detail, and based on a combination of the previous knowledge and the data interpretations we establish and present the GEC of LOOP 2.

2. Regional geological setting

2.1 The structural framework

The Sorgenfrei-Tornquist Zone (STZ) in northern Denmark is interpreted as a tectonic structure separating the Danish Basin from the Fennoscandian Shield (Hansen et al., 2000). The STZ is a deep-seated fault zone between two crustal blocks and it is bounded by the The Fjerritslev fault to the south and by the Børglum fault to the north (Figure 1). The STZ was formed in the Pre-cambrian and the structure has occasionally been active until the present day (Mogensen and Korstgård, 2003).

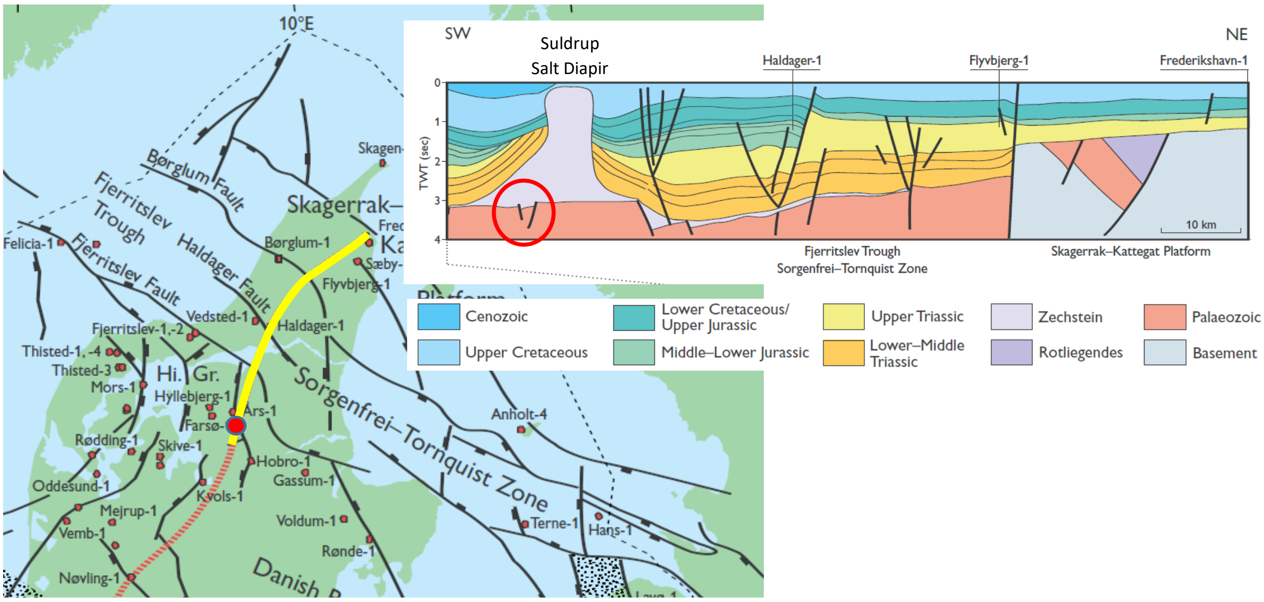

Figure 1: Map showing deep exploration wells (red dots), major deep faults (black lines) and a SW-NE profile (insert) along the yellow line on the map. The red dot marks the location of LOOP 2 and the red circle marks faults in the top pre-Zechstein surface. TWT = Two-Way Travel time (seconds). Adapted from Nielsen (2003).

The major fault orientation is NW–SE, but several NNE–SSW to NNW–SSE-trending faults are present inside as well as outside the STZ, for instance the faults forming the Hyllebjerg Graben (HG on Figure 2). According to Koyi & Petersen (1993), model results find that salt accumulate over the basement faults of this graben resulting in the formation of the Suldrup and Hvornum salt diapirs along the eastern flank of the Hyllebjerg Graben (Figure 2). The faults under the Suldrup and Hvornum salt diapirs are part of a zone of NNE-SSW to NNW-SSE trending faults in the top pre-Zechstein as visualised on Figure 2, and apparently this fault zone passes through the LOOP 2 area (Figure 3). Figure 3 also shows mapped faults in the basement with WSW-ENE to SW-NE oriented faults. The faults of the Hyllebjerg Graben and the Suldrup salt diapir are sketched to the left on the profile in Figure 1.

According to Brandes et al. (2018), faults of the STZ have been reactivated during the Lateglacial as a result of the weight relief from the Scandinavian Ice Sheet, and studies from Germany have shown that the loading and unloading of glacier ice also can create movements in salt structures (e.g. Al Hseinat et al. 2016; Lang et al. 2014). The result can be movement along faults and deformation of sediments above in Lateglacial and postglacial times.

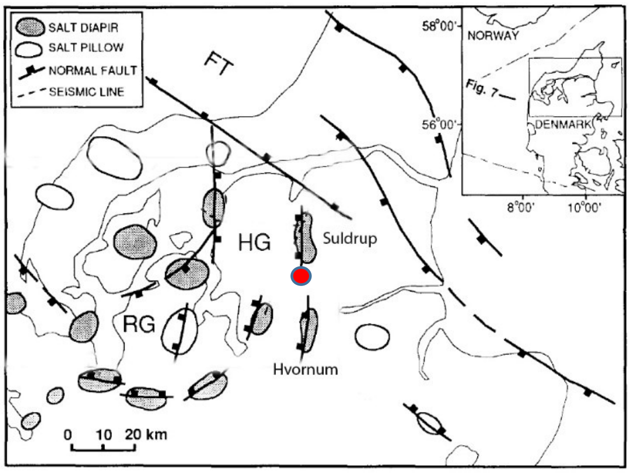

Figure 2: Simplified map with location of major basement faults as black lines and salt structures shown as grey shaded areas. FT = Fjerritslev Trough; HG = Hyllebjerg Graben; RG - Rødding Graben. A red dot marks the location of the LOOP 2-area. Modified after Koyi & Petersen (1993).

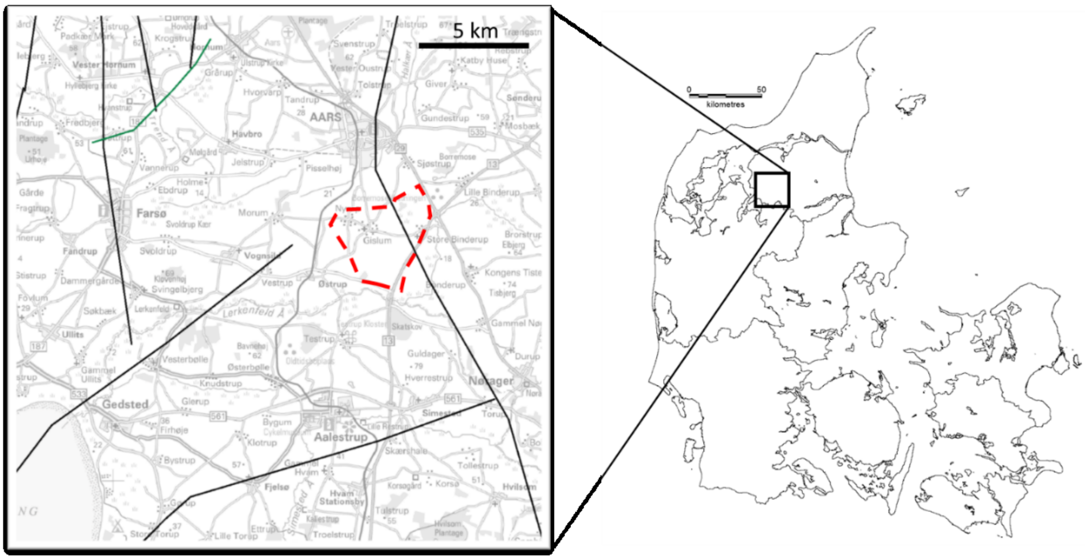

Figure 3: Faults of the Top pre-Zechstein (black lines) and Top Triassic (Green lines). Faults from Vejbæk & Britze (1994) and Japsen & Langtofte (1991), respectively. Red hatched polygon marks the LOOP 2 area.

2.2 The pre-Quaternary geology

The oldest sediment of the Cenozoic succession (Figure 1) is the Danian limestone (Clausen & Huuse 1999). On top of the limestone rests a succession of dense Palaeogene marine clays which for the youngest part contains silts and sands (Heilmann-Clausen 1995). Miocene sediments were probably deposited in the area, but northern Denmark was affected by tectonic movements during the Neogene and the uplift probably led to substantial erosion prior to the erosion by the Pleistocene glaciers (Japsen et al. 2002). The Pre-Quaternary succession was probably faulted along the fault zones of the Hyllebjerg Graben.

2.3 The Quaternary geology

The Quaternary succession in Denmark is formed as the result of erosion and deposition in a climate fluctuating between cold and warm conditions. During the Pleistocene, several glaciations affected Denmark, but only the three latest glaciations have left an unquestionable mark on the subsurface. Sediments from the oldest of the three, the Elster glaciation, is only found at a few sites on the island of Funen and in Jutland, whereas sediments from the following glaciation, the Saalian, are very common in the near-surface of Jutland, west and south of the Main Stationary Line (MSL). The MSL represents the maximum extent of the youngest glaciation, the Weichselian, and thus the areas east and north of it represents the youngest glacial deposits (Houmark-Nielsen et al. 2005). The warm periods between the glaciations are the Holstein interglacial, the Eemian interglacial and the present interglacial, the Holocene.

The LOOP 2 study area lies in the Himmerland region, which has been overridden by glaciers several times during the last three glaciations. Today's landscape in the region is dominated by the action of ice and meltwater during the Weichselian and is characterized by presence of prominent open tunnel valleys, outwash plains and ice-marginal hills. The LOOP 2 area is located partly in a hilly glacial terrain and partly on a small outwash plain formed in front of the last Weichselian ice-sheet (Smed, 1979). The outwash plain is surrounded by ice-marginal hills.

The latest ice-advances that reached the area during the Mid-Late Weichselian was the 'Kattegat advance' from the north c. 29-27.000 years ago, the 'Main ice advance' from northeast c. 23-21.000 years ago, and finally an easterly re-advance 19.000 years ago (Larsen et al. (2009). It seems obvious, that these ice advances are responsible for most of the geomorphological features and the uppermost sediments in the study area. The W-E to NW-SE oriented hills were probably formed by oscillations of the receding Main advance. The outwash plain between the ice-marginal hills was formed either in relation to this advance or the latest advance just a few thousand years later.

In many places, deep tunnel valleys have been eroded into the subsurface by meltwater under high pressure underneath the glaciers (Jørgensen & Sandersen 2006). When the ice melted away, the typically 1-1½ km wide and up to 400 m deep valleys were filled with sandy and clayey sediments. In Himmerland, a number of buried valleys have been mapped, but no valleys have hitherto been found in the study area. Just a few kilometres to the north, at Aars, a small number of valleys between ½ and 1 km wide and with depths of up to 100 m have been found (Sandersen & Jørgensen 2016). The valleys are dominated by orientations around N-S to NNE-SSW, but an ENE-WSW orientation has also been found. These orientations also characterise the valleys and the low-lying areas in the present-day terrain. The mapped valleys may represent several generations, but the two orientations match well the orientations of the youngest ice-advances mentioned above.

Some of the tunnel valleys in Himmerland that were not completely filled with glacial sediments, have been flooded by the sea during the Holocene. Occurrences of marine sediments between glacial sediments in the valley infill shows that the same presumably has happened during earlier interglacials. This also points to extensive re-use of older valley traces during subsequent ice advances (Sandersen & Jørgensen 2012, 2016).

3. Geology and Geological Elements

The geology in LOOP 2 has been mapped with the towed Transient ElectroMagnetic method (tTEM) and boreholes as described in Sandersen & Kallesøe (2021). The new data has been combined with existing data and high-resolution digital elevation models based on LiDAR data. Highlights from the results of the mapping followed by a subdivision of the sedimentary succession are presented in the following.

3.1 Geological mapping of LOOP 2

- **The tTEM mapping** has added significant knowledge of the geological setting and has especially provided a good resolution of individual layers and the surface of the good conductor (Palaeogene clays). Even though most of the boreholes are shallow, there is a good correspondence between the geophysical and the geological data.
- **The sedimentary succession** shows Pre-Quaternary clay with an undulating surface in a large part of the study area. Above, a Quaternary succession consisting of tills, meltwater sands and clays, and local occurrences of postglacial freshwater deposits were found.
- The topography of the surrounding areas shows pronounced ice-marginal hills, so **glaciotectonic deformations** in the hilly parts are expected. Older glaciotectonic deformations of the deeper parts of the subsurface is highly likely, and rafts of pre-Quaternary sediments in boreholes have been described. In addition, the very complex infill of the buried valley to the north points to deformation.
- Signs of **tectonic deformation** of the Lateglacial outwash plain sediments points to events happening after the outwash plain was formed and the ice had melted away. These tectonic disturbances could be caused by movements along deep-seated faults.
- A more than 1 km wide, deeply eroded **buried valley** with a very varied infill is found in the north-western part of the study area. Also, a 400 m wide buried valley predominantly filled with sand and gravel is found to the east.
- Because of a limited number of deep boreholes and the limited penetration depth of the tTEM, the geology below -50 m a.s.l. remains largely unknown. However, correlations between terrain features and subsurface structures has paved the way for connecting the formation of the near-surface geology with sediments and structural features of the deeper subsurface.

3.2 The sedimentary succession and the delineation of 'Geological Elements'

In the MapField project, we introduce 'Geological Elements' (GE's) in the geological mapping and modelling workflow. GE's are defined as '*separate volumes of the subsurface representing groups of layers that can be related to specific parts of the geological history of the area, thus having separate formation histories*.' More on the definition of GE's, a description of the delineation, and the 3D modelling of GE's can be found in Sandersen & Kallesøe (2021).

Four Geological Elements (GE) have been delineated in the LOOP 2 area. The four geological elements are sketched in Figure 4 and described in the following. Used data are existing geophysical data, geophysical data collected as part of the MapField project, borehole data and LiDAR Digital Elevation Models (DEM). A description of the data is not included in this report and instead we refer to Sandersen & Kallesøe (2021).

Important structural features in the area are two N-S and ENE-WSW oriented buried tunnel valleys which have been mapped by the tTEM (see Figure 4). The orientations of the buried valleys closely match the valley-orientations found at Aars. The valleys are eroded to around 70 to 90 m b.s.l. where the northernmost valley presumably is eroded through the Palaeogene sediments. The infill of the two valleys dominate the Quaternary sedimentary succession below 10 m b.s.l.

3.2.1 Geological Element GE1: Pre-Quaternary clays

Lithology
The deepest and oldest parts of the sedimentary succession within reach of the boreholes in the area consist of light olive grey sticky clay from the Eocene (e.g. borehole DGU no. 40.1006). Above, layers of dark greenish-grey glauconitic mica clay of presumably Oligocene age are found (e.g. DGU no. 40.1006, 40.537). In total, only 14 m of this pre-Quaternary succession has been penetrated.

Occurrence
Judged from boreholes and geophysical data, the top surface of the pre-Quaternary sediments varies from 15 m a.s.l. to deeper than 83 m b.s.l. The deepest parts are found underneath the buried valleys and the shallowest parts constitute a plateau between 15 and 25 m b.s.l. and a smaller 'knoll' reaching as high as 15 m a.s.l. (Figure 4 at the centre and to the right, respectively).

The Pre-Quaternary sediments are more or less surrounded by the deeply eroded buried valleys which make the sediments stand out as an erosional remnant (Figure 4). The boundary to the Lower Palaeocene Limestone below is not mapped, and in borehole DGU 40.1022, the limestone is not reached at 83 m b.s.l. According to boreholes north and west of the area, the limestone can be found at depths of around 50 to 70 m b.s.l. (e.g. borehole DGU no. 48.805). There is a general dip of the limestone to the south (Clausen & Huuse, 1999) and the top of the limestone is therefore most likely found between 80 and 100 m b.s.l. in the area.

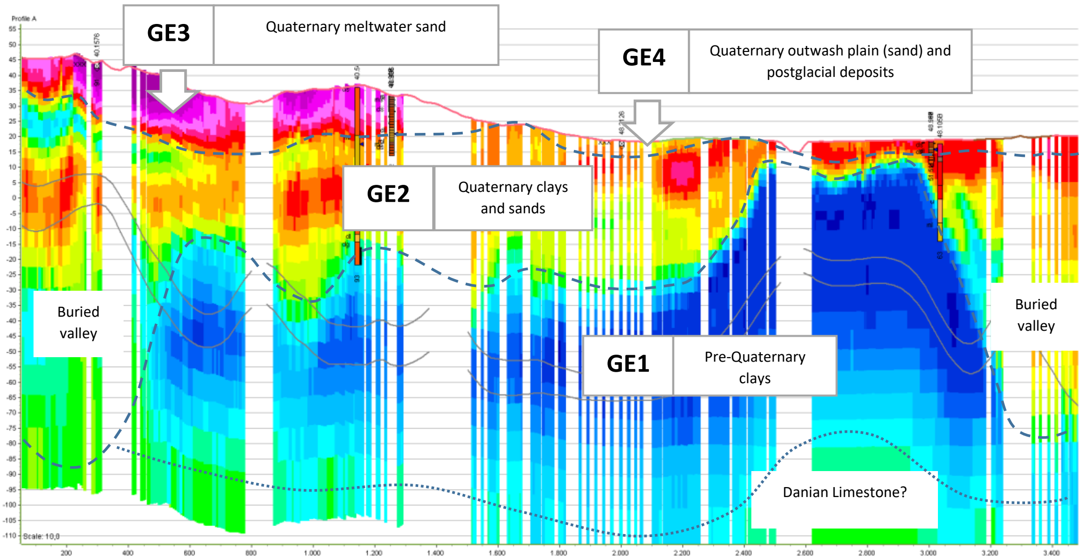

Figure 4: Geological Elements GE1 to GE4 shown on Profile A (NW-SE) in the southern part of LOOP 2. The tTEM resistivity models are shown as coloured vertical lines (blue/green: low resistivities; yellow/red/purple: high resistivities). A few boreholes are shown as isolated vertical rods.

Formation

The sediments are Palaeocene to Oligocene marine clays deposited in the Norwegian-Danish Basin (Heilmann-Clausen 1995). Sediments of these types can be found in large parts of the country where they usually constitute the deep low-resistive layer in TEM surveys (e.g. Sandersen & Jørgensen 2012).

The upper boundary of the sediments is generally erosional reflecting an extended period of erosion from the Upper Miocene to the Quaternary.

3.2.2 Geological Element GE2: Quaternary sequence in and above buried valleys

Lithology

GE2 (see Figure 4) is a Quaternary sequence consisting of a deep part representing the infill of the incised buried tunnel valleys and an upper part consisting of clays and sands at levels above the buried valley incisions (see Figure 4). The valley infill is only penetrated by a few boreholes, and according to boreholes DGU no. 40.918 and 40.1022, the infill is dominated by clay tills, with a few layers of meltwater sand. The clay contains isolated slabs of pre-Quaternary clay, which presumably explains the occasional very low resistivities within the valley infill.

Above the valley infill, the GE2 is a succession of meltwater sand, clay till and meltwater clay. The clay tills are lithologically varied, but most often silty and sandy, whereas the meltwater clays are fine-grained and occasionally silty. In some areas, the clay tills have unusually high resistivities in the tTEM data (>60 ohmm) reflecting a high silt and sand content. For example, in borehole DGU 40.1006 the clay till is described as *"Weakly silty, sandy, light olive grey, calcareous till. Note: Weakly gravelly".* These tills can therefore be difficult to distinguish from meltwater sand in the geophysical data.

Occurrence
The buried tunnel valley infill is seen between elevation c. -90 m to -20 m and is probably occasionally in direct contact with the limestone below. The valley infill is confined to the ENE-WSW and NNE-SSW oriented valley structures. From elevation 20 m b.s.l. and up to c. 20 m a.s.l. the succession is characterized by more extensive layers of sand and clay. In the low-lying parts of the terrain, large parts of the GE2 appears to be eroded.

Formation
The tunnel valleys were formed by erosion underneath the ice sheet during the Pleistocene glaciations, and the infill took place either under the ice, or in front of the ice margin. The succession above the valleys shows more extensive layers, and just as the valley infill, it was deposited either underneath or in front of the glaciers. Judged from the apparent deformations of the succession, the sediments have in some areas been glaciotectonically deformed and possibly also been affected by neotectonics (see later description).

The age of the succession cannot be determined because dating of sediment from the LOOP-area has not been made. However, just 2 km west of LOOP 2, the borehole DGU no. 48.805, penetrates marine interglacial clay from 11 to 31 m b.s.l. This clay has tentatively been interpreted as having a Holsteinian age (GEUS, 2020; P. Konradi). As the Quaternary sediments in the borehole lie directly upon Palaeocene Limestone, it is reasonable to conclude, that the penetrated sediments represent buried valley infill. Therefore, this valley erosion must have taken place during the Elsterian or an earlier glaciation. It is likely that the buried valleys in the LOOP 2 area close by have the same age. The shallower Quaternary sequence of GE2 is therefore most likely from the Saalian and/or the Weichselian glaciations.

3.2.3 Geological Element GE3: Quaternary sand in glacial hills

Lithology
The GE3 (see Figure 4) consists of meltwater sand and gravel with some occurrences of mostly sandy tills. The sand and gravel are generally brownish yellow and non-calcareous in the uppermost parts and calcareous in the lower parts (e.g. DGU no. 40.1376). Where the tills are lying close to terrain it is usually non-calcareous and yellowish brown, whereas deeper tills are calcareous and olive brown in colour (e.g. DGU no. 40.1374).

Occurrence
GE3 occurs predominantly in the hilly northern part of the area above 15 m a.s.l. Due to erosion, GE3 is not present in the low-lying areas to the south and east.

Formation
GE3 represents a glacial succession that presumably originally covered all of the area. The meltwater sand and gravel represent a former outwash plain, whereas the tills are deposited subglacially. The age is unknown, but most likely from the Saalian and/or the Weichselian.

3.2.4 Geological Element GE4: Weichselian outwash plain sand and postglacial sediments

Lithology

GE4 consists mainly of yellowish brown, non-calcareous to calcareous, fine to medium grained meltwater sand (e.g. DGU no. 48.1171 and 48. 2126). In some areas, the sand is covered by occurrences of grey to olive-grey postglacial freshwater gyttja and black peat (e.g. DGU no. 40.2058).

Occurrence

GE 4 occurs in the uppermost parts of the subsurface in the lowest parts of the terrain (Figure 4), especially to the south and to the northeast (yellowish and greenish colours in Figure 5). The area to the northeast is represented by the borehole DGU no. 40.2058 (yellow star on Figure 5), where c. 5 m of glacial meltwater sand is found underneath 5 m of freshwater gyttja and peat. Based on geophysical data and boreholes, the thickness of the sediments varies, but is generally less than 10 m. However, where the GE2 below is sandy as well, the boundary between the two elements is difficult to delineate.

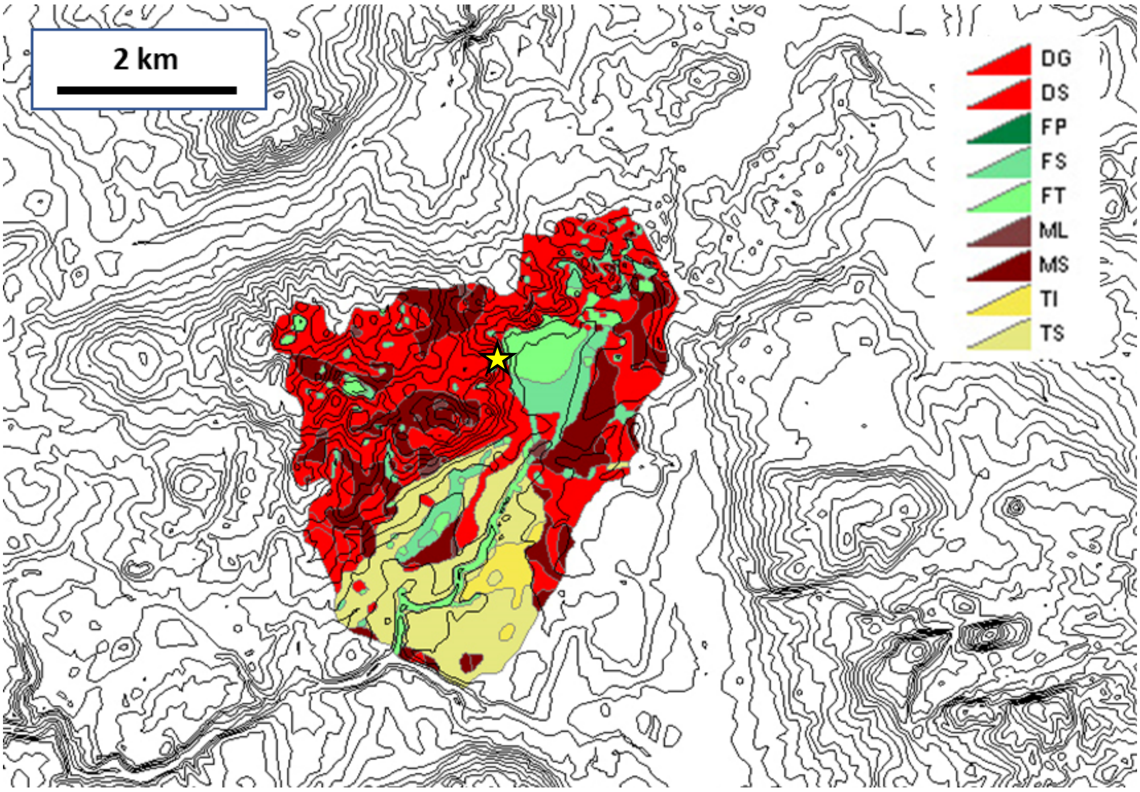

Figure 5: Soil map showing lithology of the uppermost meter of the subsurface in the LOOP 2 area (Jakobsen et al. 2011; updated map). DG/DS: Meltwater gravel/sand; FP/FS/FT: Postglacial freshwater gyttja/sand/peat; ML/MS: Clayey/sandy till; TI/TS: Extra-marginal silt/sand. Yellow star marks location of borehole DGU no. 40.2058. Equidistance of the curves of the topography is 5 m.

Formation

The sandy part of GE4 is formed in the Late Weichselian as an outwash plain in the low areas between the surrounding hills (Smed, 1979). The outwash plain sediments created a westerly sloping surface, which can best be seen in the southern part of the area. More or less isolated depressions on the outwash plain were formed in Lateglacial and/or postglacial times and in these depressions, lake gyttja and peat were deposited. In the depression to the north, the sediments show a development from a lake on the outwash plain where freshwater gyttja was deposited, to a bog with development of peat and eventually dry land as it appears today. Organic rich sediments can also be found in small patches in the hills to the north (see Figure 5; green colours).

3.3 Topographic analysis

The terrain in and around the study area is very varied showing irregularly shaped hills to the north and south, smooth hills to the east, and areas in-between changing between smooth plains, low and smoothed hilly terrain, and low-lying, irregularly formed plains. An important observation is, however, that these areas with different topographical features seem to be separated along several, more or less straight lineaments as shown on Figure 6. The most prominent of these lineaments are highlighted with arrows and hatched lines on the figure, and they appear be grouped: one with dominant orientations around N-S (lineaments 1-4; green arrows) and one around NNW-SSE (lineaments 5-7; orange arrows). Clearly visible but less dominant lineaments have orientations between WNW-ESE and SW-NE.

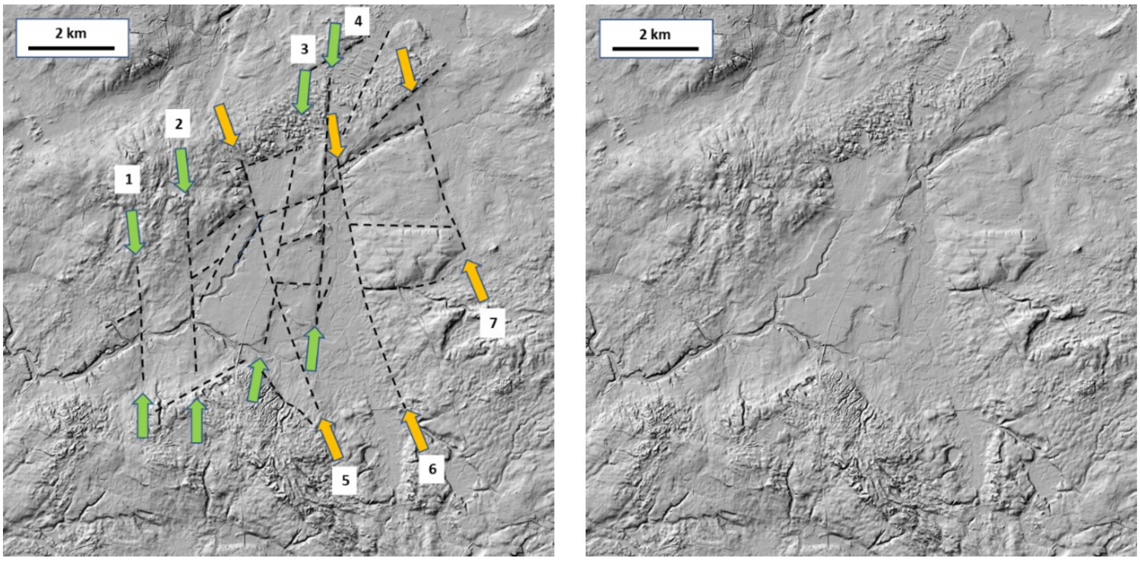

Figure 6: LiDAR hillshade image of the topography of LOOP 2 and its surroundings. To the left, lineaments are highlighted by hatched lines and numbered arrows. See text for explanation.

The lineaments divide the area in several sub-areas with varying topography in terms of elevation, smoothness, and slope. In Figure 7, eight areas labelled A to H have been selected and highlighted:

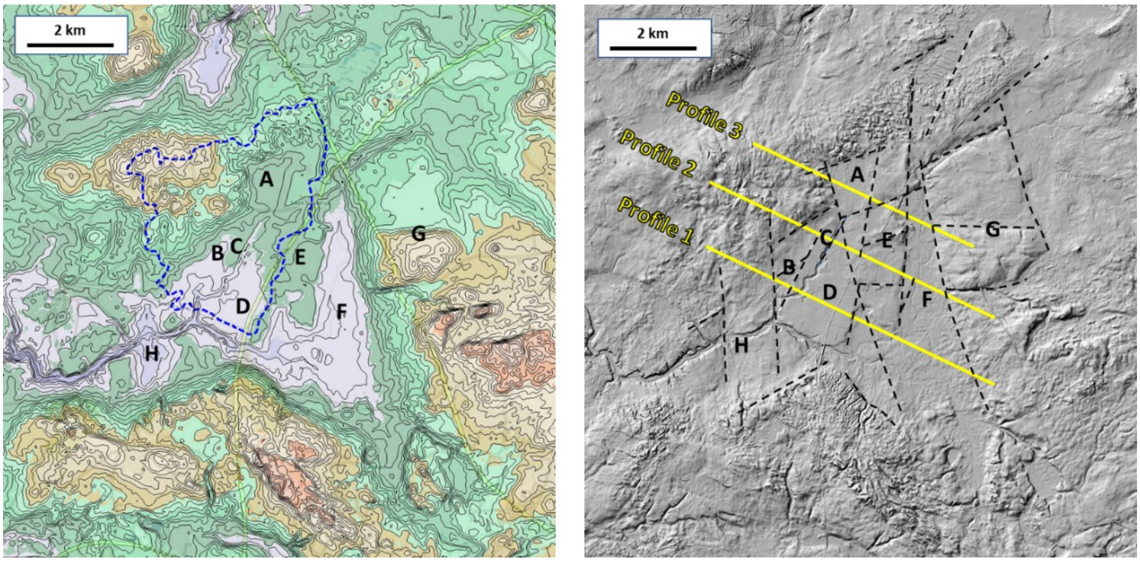

Figure 7: Topographic features in- and outside LOOP 2: To the left the topography is shown as iso-curves. Equidistance of the curves is 5 m. Blue shows the lowest part; brown shows the highest parts. To the right the lineaments mentioned in the text are highlighted with hatched lines and arrows. Letters A to H on both figures refers to the topographical sub-areas mentioned in the text. To the right, the location of the three profiles in Figure 8, Figure 9 and Figure 10 are shown as yellow lines.

<u>Sub-area A:</u> A westward sloping area, surrounded by hilly or higher-lying areas. The area slopes toward the western hills and is interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011). Up to 5 m thick postglacial gyttja and peat can be found in his area.

<u>Sub-area B:</u> A SW-NE depression on the outwash plain with only minor post-depositional stream erosion. It has a sharp boundary to the outwash plain to the southeast (Sub-areas C and D). The area is interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011).

<u>Sub-areas C and D:</u> Interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011). Sub-area D is the largest part of the plain, and it is lying a few meters higher than Sub-area B. The D-area has a south-westerly oriented slope in the northern part and a north-westerly oriented slope in the southern part. A remarkable feature on the plain is the south-westerly oriented stream erosion. The Sub-area C is a small area that lies 1-2 m above the D-area and has rather sharp boundaries to both sub-areas B and D. To the southwest, the C-area joins smoothly with the D-area.

<u>Sub-area E:</u> This area is an irregularly formed area bounded by the lineaments 3 and 4 on Figure 6. To the north, the area shows smoothed hills and to the south slightly elevated and a more irregular surface compared to the neighbouring D-area. The sub-area E appears to be crossed - and thereby split up - along subtle W-E to WSW-ENE lineaments. The area is interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011).

<u>Sub-area F</u>: This sub-area is sharply defined by the lineaments 4 and 6 (Figure 6 and Figure 7) and shows a triangular plain lying significantly deeper than the surface of the outwash plain of sub-area D. The area is interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011). The F-area has a smoothed surface with irregularly formed parts – especially to the south. The slope within the area shows varying orientations.

<u>Sub-area G</u>: Sub-area G constitute a smooth hilly area between the lineaments 6 and 7, that seems to be split up by W-E to SW-NE lineaments (Figure 6 and Figure 7).

Sub-area H: The sub-area H just southwest of LOOP 2 is a 2 km long and N-S oriented, hilly area between the lineaments 1 and 2 in Figure 7. The lowest lying parts of the area is interpreted as an outwash plain (Smed 1979; Jakobsen et al. 2011). Along the lineament 1 to the west, a N-S depression is present between the low, smooth hills on both sides. A remarkable feature of this sub-area is, that a stream cuts perpendicularly through both the depression and the surrounding hills along an almost straight line (Right above the 'H' on Figure 7).

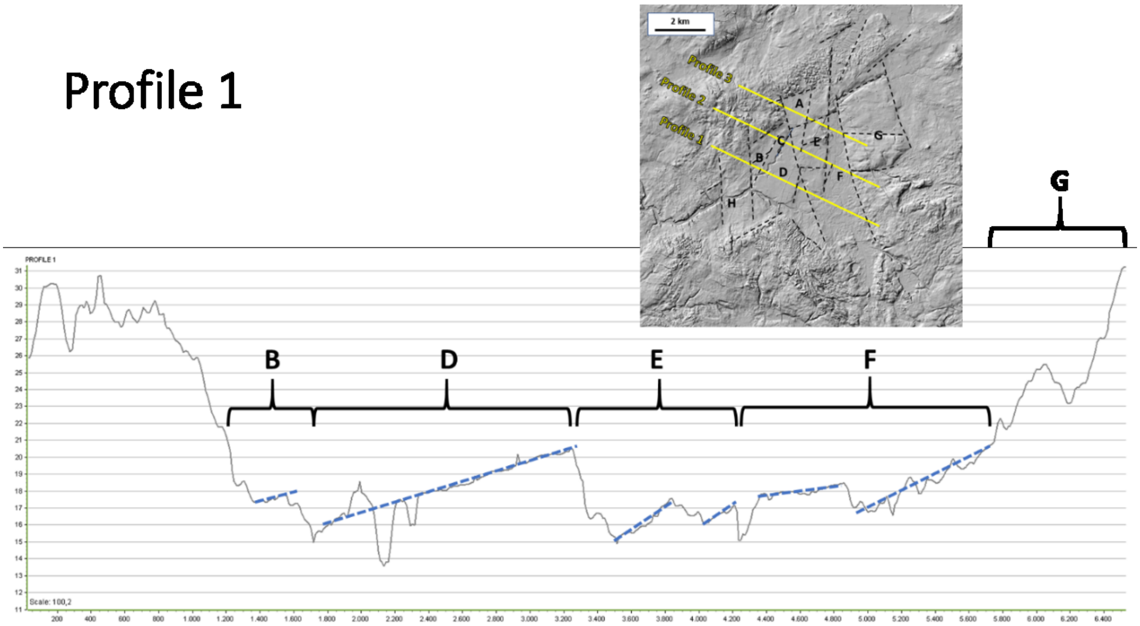

Figure 8: Topographic NW-SE Profile 1. The letters refer to subareas shown on Figure 7. Slope trends are highlighted with hatched blue lines. Note: Vertical exaggeration X100.

To illustrate the differences between the sub-areas described above, three profiles crossing the area are shown in Figure 8, Figure 9 and Figure 10:

- On Profile 1 (Figure 8), the westerly slope of the outwash plain of sub-area D is clearly seen, and apparently a similar trend can be seen in the neighbouring sub-areas. The rather sharp boundaries between the sub-areas are apparent on the profile creating a saw-tooth appearance. The outwash plain between the hills is clearly divided into separate westerly sloping sections which also show different elevations.
- Profile 2 (Figure 9), 1½ km northeast of Profile 1, shows a remarkable change in the dominant slope orientation of the sub-areas from westerly to easterly oriented slopes.
- Profile 3 (Figure 10) shows the sharp boundaries between the sub-areas, and also the borehole DGU no. 40.2058 that reveals a 5 m thick sequence of postglacial gyttja and peat above meltwater sand. According to the tTEM data, it appears that the bottom of the (generally low-resistive) postglacial sediments dips towards west as indicated on the profile. The meltwater sand below is interpreted to represent the top of the coarse outwash plain sediments which therefore lies as deep as 17,5 m a.s.l. at this point.

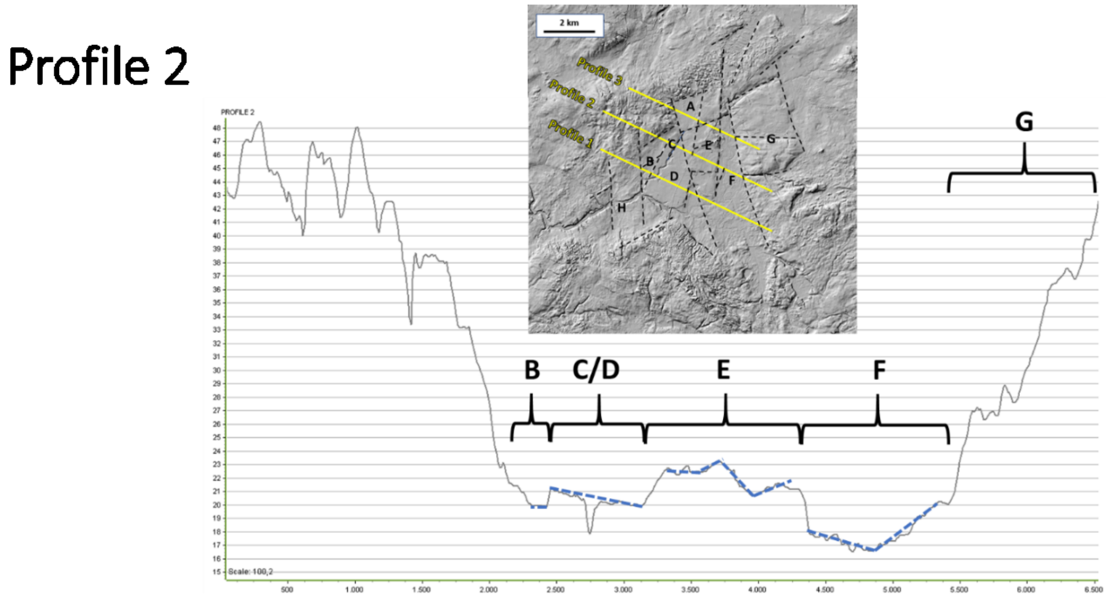

Figure 9: Topographic NW-SE Profile 2. The letters refer to subareas shown on Figure 7. Slope trends are highlighted with hatched blue lines. Please note: Vertical exaggeration X100.

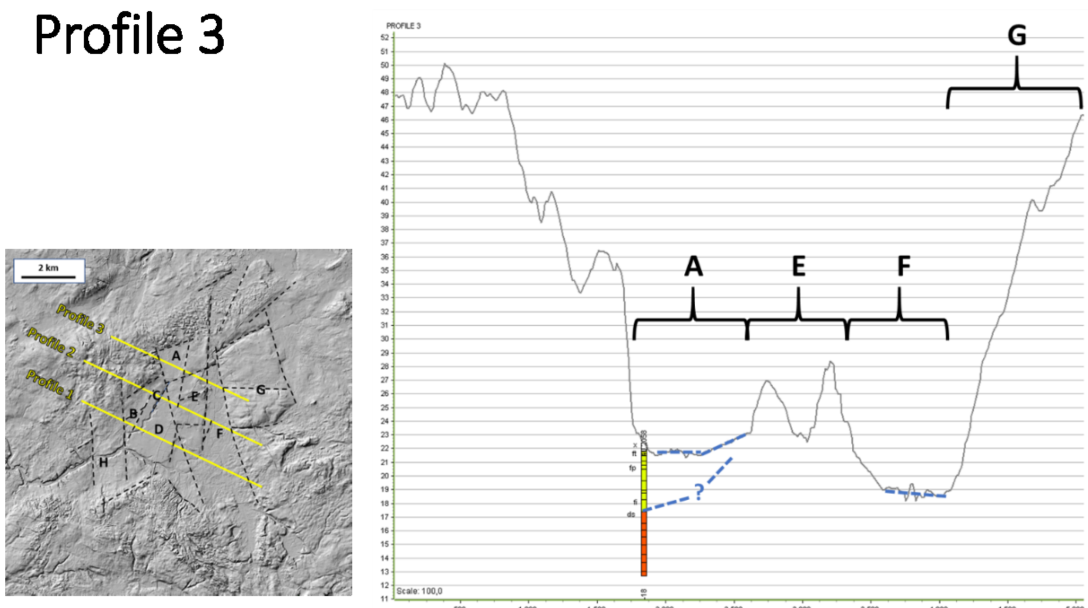

Figure 10: Topographic NW-SE Profile 3. The letters refer to subareas shown on Figure 7. The red and green coloured vertical rod marks the borehole DGU no. 40.2058 (red: ds; meltwater sand; fi, fp, ft: freshwater silt, gyttja and peat). Slope trends are highlighted with hatched blue lines. Please note: Vertical exaggeration X100.

3.4 Discussion

The geology of the LOOP area is complex in terms of both architecture and the types and the distribution of sediments. The formation of the geological succession is a result of sedimentation under marine conditions during the Palaeogene and very varied episodes of erosion and deposition during the Neogene and the Pleistocene. As interpreted from the available data, this event chronology, however, appears to have included several tectonic events.

The topography of the study area and its surroundings is characterised by up to 6 km long straight lineaments that split the area into separate sub-areas that differs highly from each other in terms of elevation, smoothness, and slope. In addition to this, the area features low-lying areas of which some show rather thick deposits of postglacial lake gyttja and peat (especially sub-area A). The area pointed out as an outwash plain by Smed (1979), does not have the expected features of an outwash plain apart from the smooth sloping surface of some sub-areas and the predominantly sandy sediments. Erosional scarps on an outwash plain would be expected between meltwater stream beds and the surrounding plain, and between erosional remnants of older sediments and the younger outwash plain. However, the complexity of the highly segmented area between the hills does not fit well into a series of geological events of deposition and erosion solely involving a receding ice sheet and its evacuated meltwater.

The mapped faults in the pre-Zechstein (Figure 3) combined with occurrence of salt diapirs close to the study area and probably a salt pillow right underneath it (Vejbæk & Britze 1994), points to a possibility of a structural control on the sediments above. As mentioned earlier, deep-seated faults can be reactivated, and deep salt structures can be mobilized by the loading and unloading of the Pleistocene ice-sheets (Al Hseinat et al. 2016; Brandes et al. 2018; Lang et al. 2014; Sandersen & Jørgensen 2015; Sandersen et al. 2021). These types of events will therefore be tightly connected with either the loading or the unloading – or both. In the case of the LOOP 2 area, however, the coupling with features in the topography – the deformation of the Lateglacial outwash plain – brings us to focus on events connected with the deglaciation. The observed lineaments and the orientation of the eroded tunnel valleys match the pattern of mapped deep faults in the region, pointing to erosion along fault zones that were easier to erode.

The orientations of the deep faults, the tunnel valleys, and the numerous lineaments in the topography points to a tectonic influence on the geological evolution of the area. This is backed up by the tTEM data (see Figure 11), which shows signs of faults in the near surface sediments, and by the topography, which shows highs and lows arranged in a complicated pattern that cannot be explained by simple erosion and deposition. Especially the depression of sub-area H attracts attention: The stream that enters the depression from the east has eroded right through an elongated N-S oriented hill, is crossing the depression causing only shallow erosion and thereafter cuts right through the hill on the other side. Either the stream existed before the creation of the hills and the depression, or a SW-NE fault disrupting the surface paved the way for a drainage path through the hills. Also, the depression of sub-area A is interesting, because it represents a large, triangular 'hole' that was isolated and left empty after the ice melted away, with a bottom elevation lower than the outwash plain further to the south. In postglacial times, the hole was filled with lake gyttja and peat. Similar occurrences of depressions on an outwash plain hosting lakes and bogs have been found in the southern part of Denmark. The depressions here were interpreted to be caused by reactivations of deep faults caused by the unloading of the Late Weichselian ice sheet (Sandersen & Jørgensen 2015).

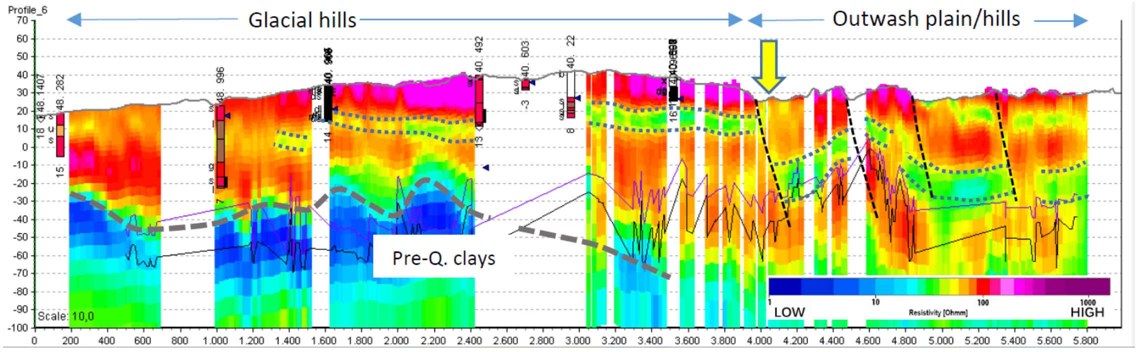

Figure 11: Southwest-northeast profile across the LOOP 2 area (from Sandersen & Kallesøe 2020). The coloured background represents the tTEM-soundings (purple to light red: high resistivities; blue to green: low resistivities). Inferred faults are shown as sub-vertical hatched lines. The sub-area 'A' (see Figure 7) is located below the yellow arrow.

Whereas the Quaternary sediments of the subsurface in the LOOP-area were deposited and eroded by glaciers and their meltwater, it seems as if movements along deep faults have influenced the formation of the Quaternary succession and landscape as we see it today. The segmentation into sub-areas with varying surface characteristics and sharp boundaries points to common forces responsible for the present appearance in and outside the LOOP area.

We therefore suggest that simple movements along the deep faults and/or salt mobilisation in the salt structures below the area has influenced the formation of the subsurface geology. The erosion of the buried valleys presumed to be Elsterian or even older, follow the orientations of the deep faults and thereby underline that the deep influence is not limited to the time of deglaciation.

4. Establishing a Geological Event Chronology

4.1 Introduction

Before making 3D geological modelling of the LOOP-area, it is important to understand the geological setting and try to sketch a possible scenario for the formation of the geological succession of the area. The local occurrences of organic material in the LOOP area are of high importance for the modelling of the nitrate reducing capacity of the sediments and therefore an understanding of the presence of the organic material is in focus (Kim et al. 2021).

In the following, a probable GEC for the area is presented. It should be noted that the GEC is to be regarded as nothing more than conceptual sketches although they are based on actual data from the area. In a simplified form, the GEC illustrates the possible events that has led to the formation of the succession by an interplay of sedimentation, erosion, and tectonics. The GEC is relative in its chronology mainly because of lack of dating of sediments in the area. Nevertheless, an attempt has been made to relate the geological events represented by the sketches to a probable time interval.

4.2 GEC Sketches

GEC Sketch 1 - Danian limestone below predominantly Palaeogene marine clays.
The GEC Sketch 1 in Figure 12 shows the situation in early Neogene times after deposition of the Palaeogene marine clays above the Danian limestone. The succession was afterwards tilted towards south-west and subject to erosion as the result of uplift.

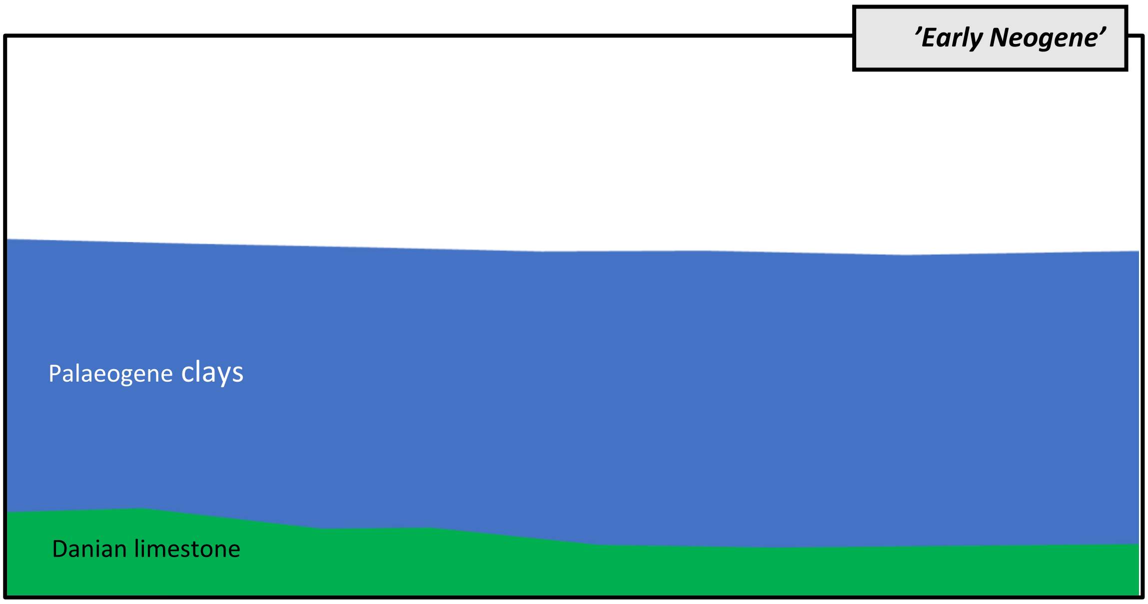

Figure 12: GEC Sketch 1 - Danian limestone below predominantly Palaeogene marine clays (Early Neogene).

GEC Sketch 2 – Tectonic movements during the Neogene

During the Neogene (Miocene-Pliocene) and presumably along with the uplift, the pre-Quaternary sequence was faulted along the old fault zones (Figure 13).

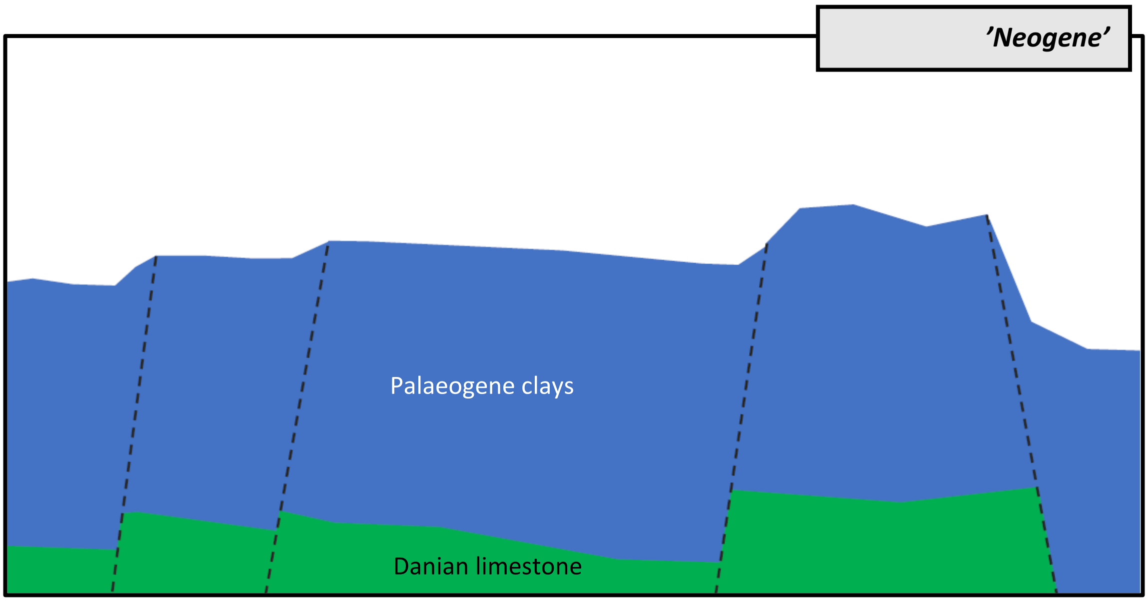

Figure 13: GEC Sketch 2 – Tectonic movements during the Neogene (Miocene-Pliocene). Faults sketched as hatched lines.

GEC Sketch 3 – Erosion by glaciers during the Pleistocene.

During the Pleistocene, the area was overridden by several glaciers and extensive erosion occurred. GEC 3 in Figure 14 shows a situation where tunnel valleys are eroded underneath an ice sheet. The valleys are presumably formed during the Elsterian or maybe an older glaciation. The valleys were most likely eroded along weak zones around faults.

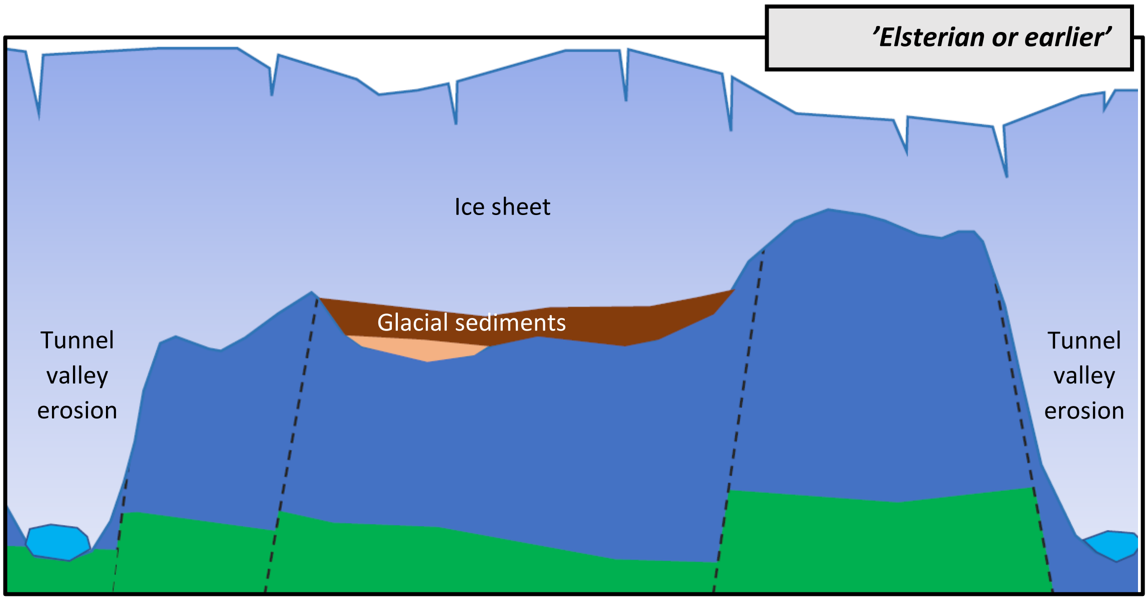

Figure 14: GEC Sketch 3 – Erosion by glaciers during the Pleistocene (Elsterian or earlier). Tunnel valley erosion is seen to the left and to the right. Deposition of glacial sediments; brown: clayey sediments (tills and meltwater clays); skin colour: sandy sediments (meltwater sand and gravel).

GEC Sketch 4 – Glacial sediments deposited by the glaciers during the Pleistocene.

After the receding of the ice sheet, the buried valleys were filled with clayey and sandy sediments (Figure 16). Floes of pre-Quaternary clays are found in the valley infill, indicative of glacial deformation. If the valleys were eroded during the Elsterian, the infill most likely represent events during the Saalian glaciation, and the sediments sketched presumably represent more than one ice advance.

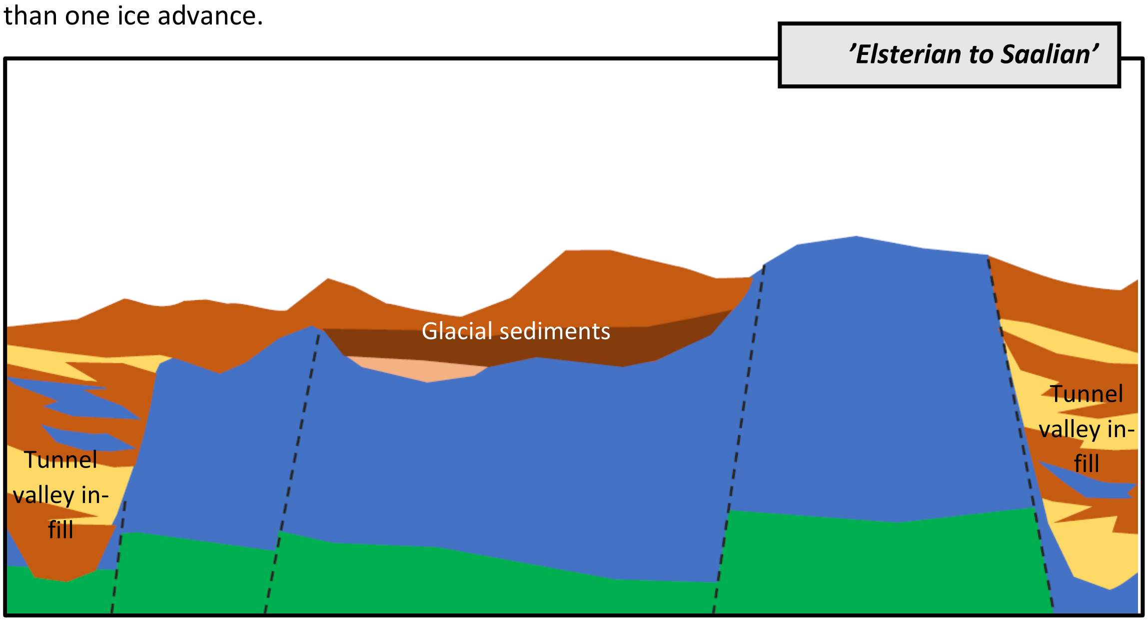

Figure 15: GEC Sketch 4 – Glacial sediments deposited by the glaciers during the Pleistocene (presumably Elsterian to Saalian). Tunnel valley infill is seen to the left and to the right. Deposition of glacial sediments; yellow: sand and gravel; brown: tills and meltwater clay; blue: floes of Palaeogene clay.

GEC Sketch 5 – Glacial meltwater sand and gravel sediments deposited in front of a glacier.

Predominantly meltwater sand was deposited during a new ice advance during the Saalian or possibly in the Middle Weichselian (Figure 16).

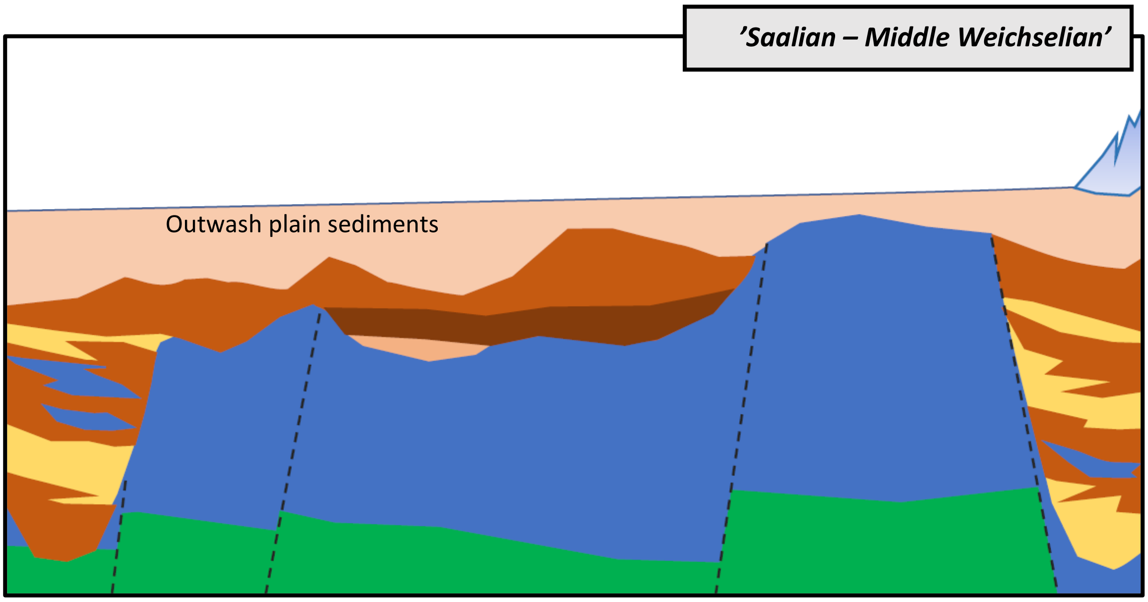

Figure 16: GEC Sketch 5 – Glacial meltwater sand and gravel sediments deposited in front of a glacier (probably Saalian to Middle Weichselian). Deposition of glacial sediments; yellow: sand and gravel; skin colour: meltwater sand; brown: tills and meltwater clay; blue: rafts of Palaeogene clay;

GEC Sketch 6 – Widespread layer of till deposited underneath a glacier.

A clay layer (mainly till) was deposited above the meltwater sand (Weichselian?); Figure 17.

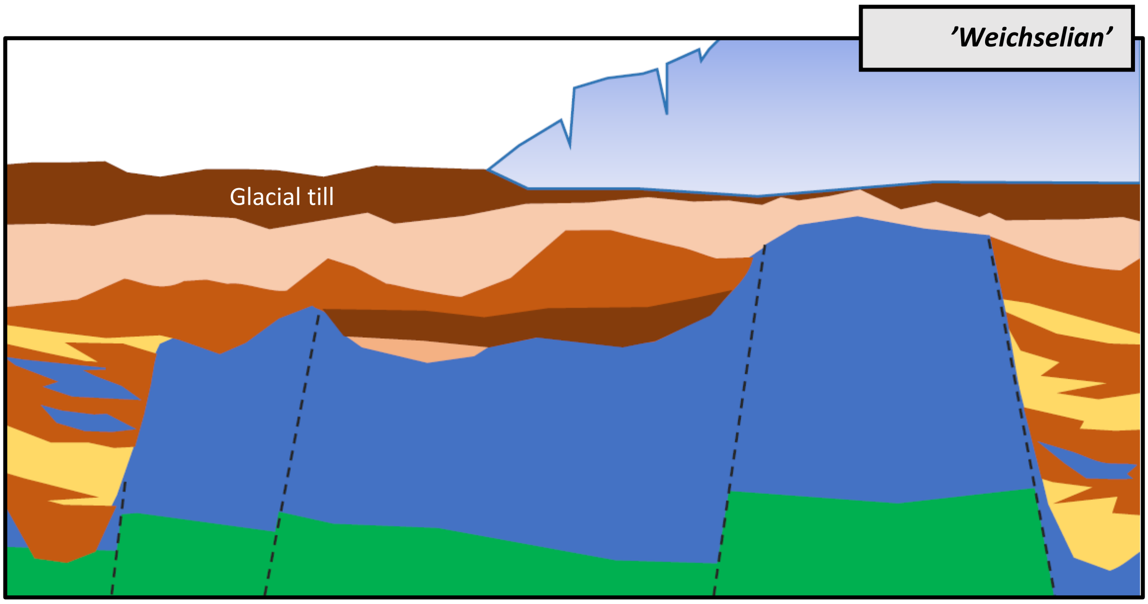

Figure 17: GEC Sketch 6 – Widespread layer of till deposited underneath a glacier (Weichselian?).

GEC Sketch 7 – Deformation of the glacial sediments by an advancing glacier.

The layers – at least in the upper parts of the succession - were deformed by an advancing glacier (Weichselian?); Figure 18.

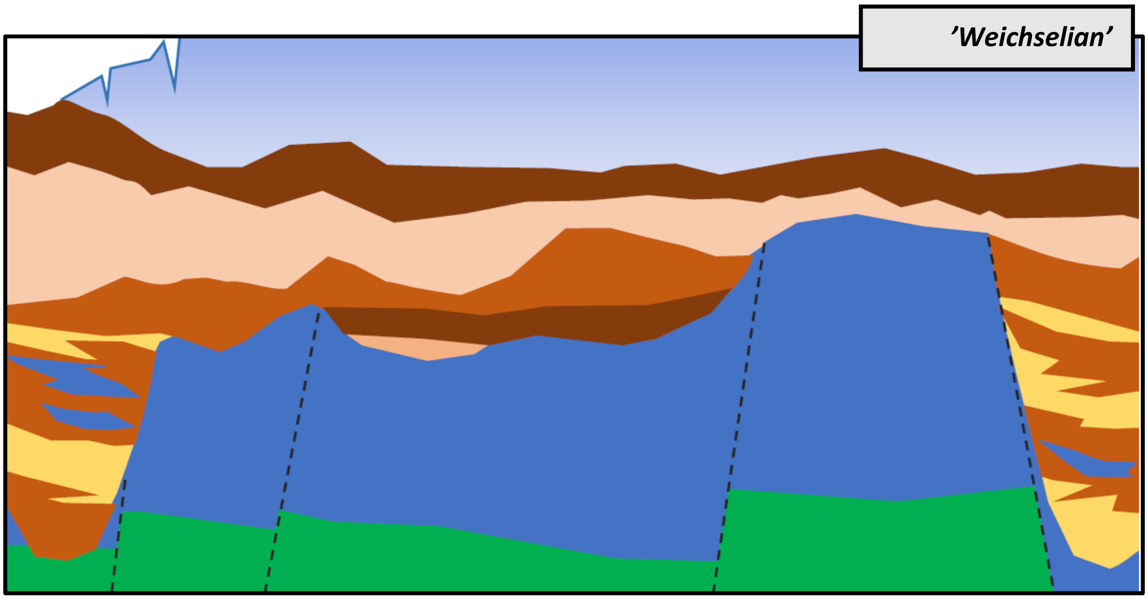

Figure 18: GEC Sketch 7 – Deformation of tills by an advancing glacier.

GEC Sketch 8 – Tectonic movements.

Tectonic movements along main fault lines – probably during the Weichselian - result in faulting and uplift of parts of the Pre-Quaternary sequence, causing the Quaternary sediments above to be deformed and dissected by faults (Figure 19). This tectonism is probably related to either salt tectonics or deep tectonic movements – or both – most likely following the recession of an ice sheet.

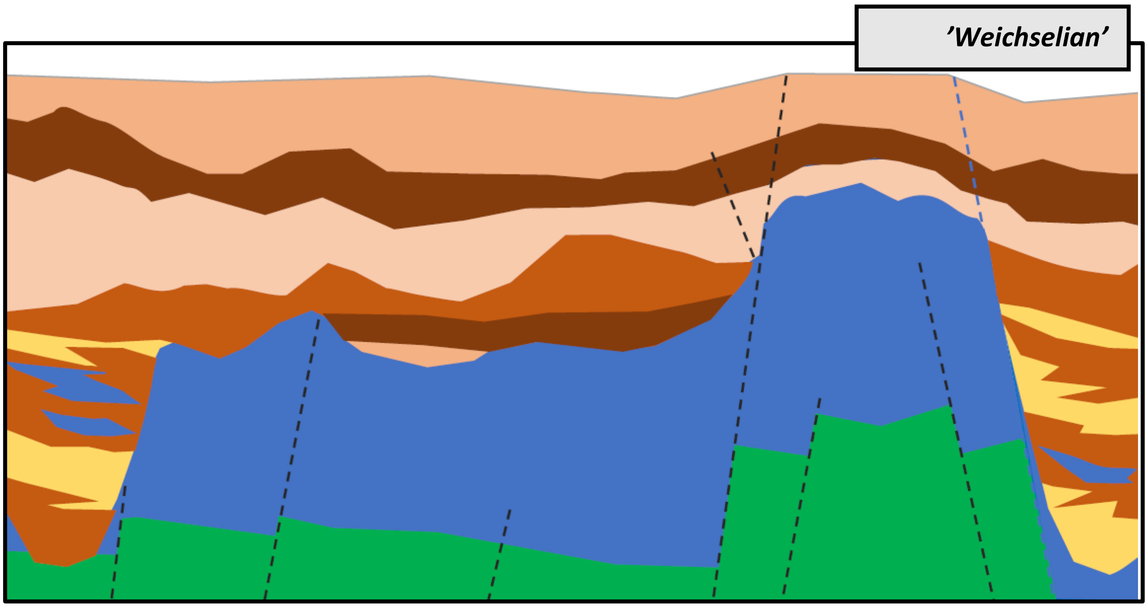

Figure 19: GEC Sketch 8 – Tectonic movements (Probably Weichselian). Parts of the Pre-Quaternary sequence are faulted and uplifted, causing the Quaternary sediments above to be deformed and dissected by faults.

<u>GEC Sketch 9 – Erosion by glacier ice and meltwater.</u>

Erosion by a renewed ice advance during the Weichselian. The erosion was probably more intense where the sediments were uplifted and faulted (Figure 20). This ice advance was most likely the last to override the area in the Late Weichselian.

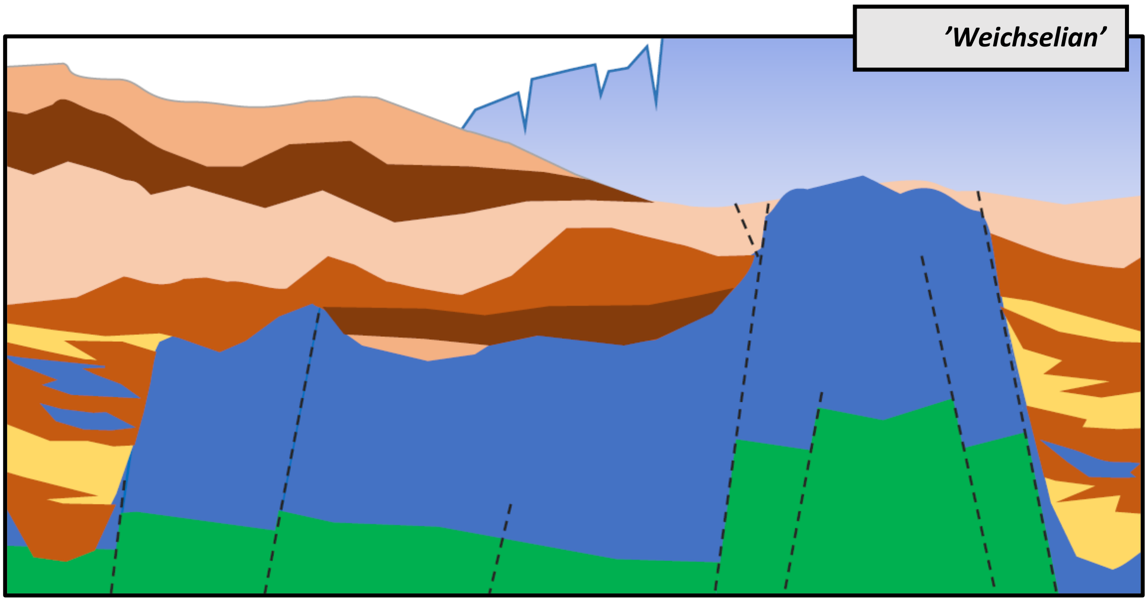

Figure 20: GEC Sketch 9 – Erosion by glacier ice and meltwater (Weichselian). Erosion was probably more intense where the sediments were uplifted and dissected by faults.

GEC Sketch 10 – Sedimentation of sand and gravel on an outwash plain in front of a glacier.
An outwash plain was formed in the lowest parts of the area in front of the receding ice sheet (Late Weichselian); Figure 21.

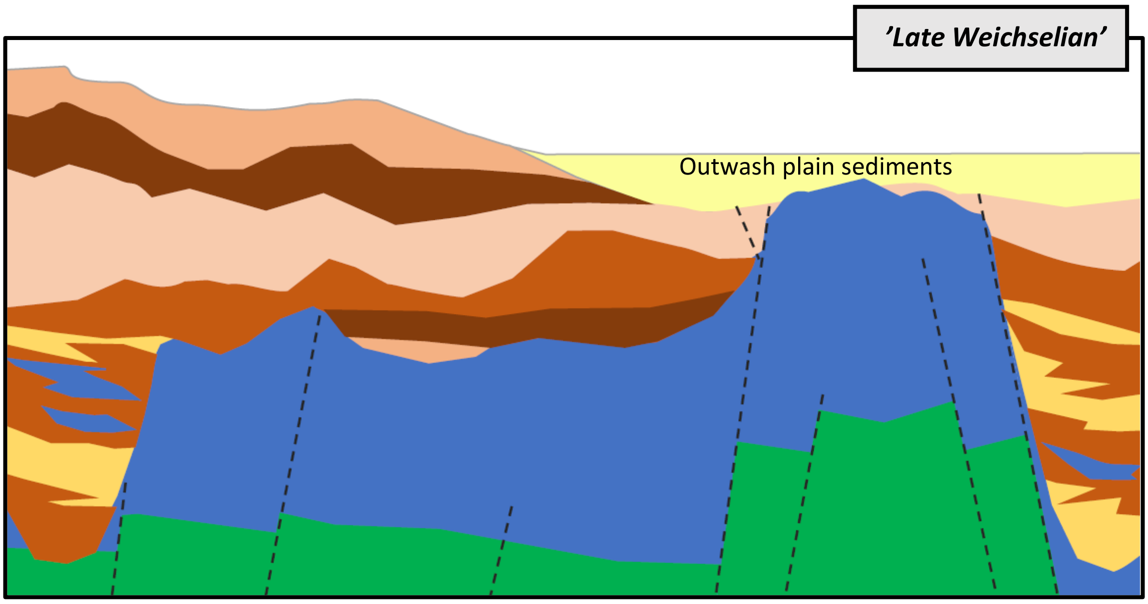

Figure 21: GEC Sketch 10 – Sedimentation of sand and gravel (yellow layer) on an outwash plain in front of a glacier.

GEC Sketch 11 – Tectonic movements along faults following deglaciation
Tectonic movements along faults following deglaciation caused parts of the near-surface Quaternary sediments to be deformed. Lows and highs were created, with postglacial sedimentation of lake gyttja and peat in low-lying areas (Figure 22).

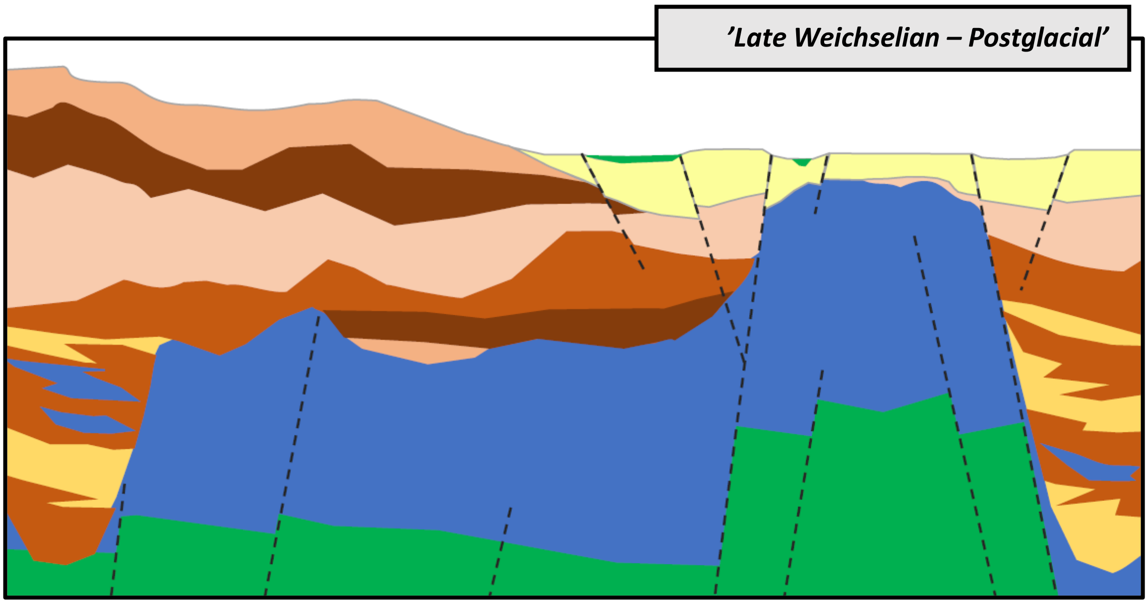

Figure 22: GEC Sketch 11 – Tectonic movements along faults following deglaciation caused parts of the near-surface Quaternary sediments to be deformed (Late Weichselian). Lows and highs were created, with sedimentation of lake gyttja and peat in low-lying areas (Postglacial; near-surface green colours).

In Figure 23, the boundaries of the four geological elements have been added to the sketched succession, and Figure 24 shows the cross-section on which the GEC sketches shown above have been based.

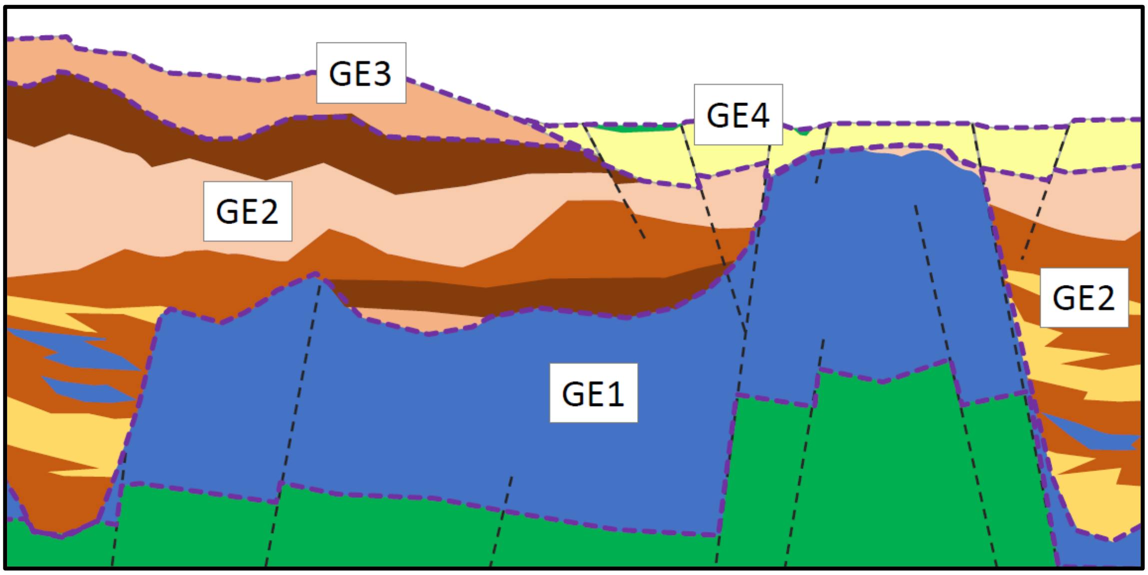

Figure 23: An illustration of the Geological Elements GE1-GE4 in the LOOP 2 area.

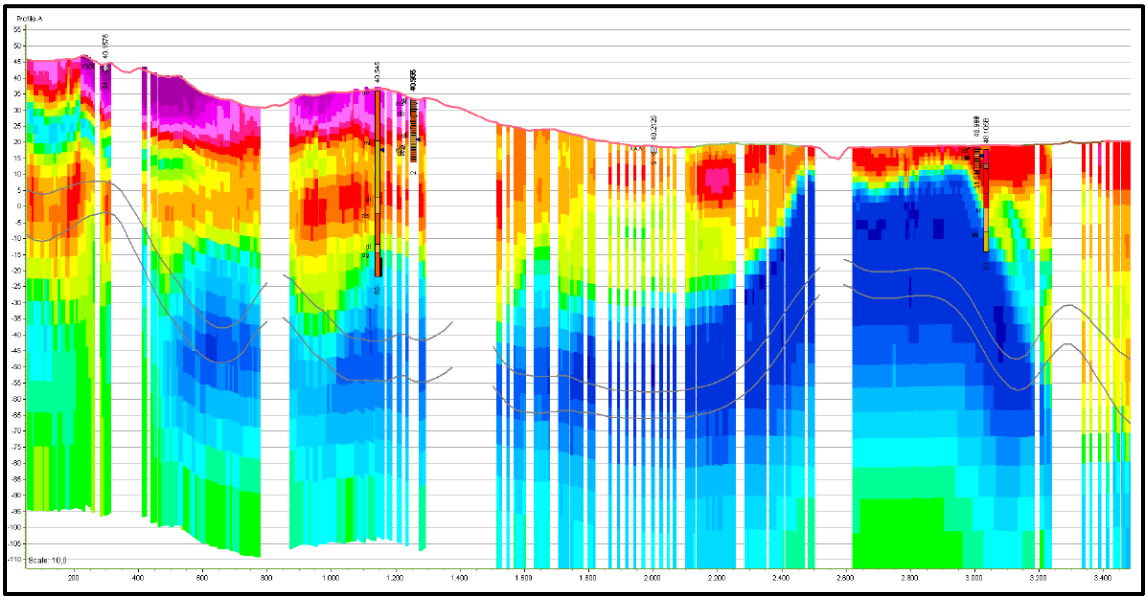

Figure 24: The NW-SE profile through LOOP 2 on which the event chronology in Figures 11-22 is created. TTEM is visualised as single resistivity soundings, where purple/red/orange colours represent high resistivities, and blue/green colours represent low resistivities. A few boreholes are shown as single rods on the profile as well. See also Figure 4.

5. Conclusions

A highly complex architecture of the subsurface in and around the LOOP 2 area has been revealed by joint interpretation of tTEM data, borehole data, a detailed digital elevation model, and a surface geology map. The mapping has given important knowledge of the geological succession and the formation history of the area. The Geological Event Chronology and the resulting 3D delineation of four Geological Elements are used in the subsequent modelling in the LOOP 2 area. A thorough understanding of the series of geological events that led to the formation of the subsurface is an important prerequisite for building of a reliable 3D geological model.

The subsurface is interpreted to be formed by sedimentation, erosion and deformation during the Palaeogene and Neogene (marine and continental environments), and during the Pleistocene (glacials and interglacials). However, the highly segmented topography in the area and the apparent layer offsets revealed by the tTEM data suggest that the formation of the subsurface cannot entirely be the result of erosion and deposition caused by glaciers. Although the area is affected by glaciotectonism, we interpret the occurrence of kilometre long lineaments and the segmentation of the lateglacial outwash plain to be caused by movements along deep faults and/or salt mobilisation. This reactivation is tentatively interpreted to be caused by the loading and unloading of the Pleistocene ice-sheets. As the erosion of the buried valleys in the area seem to follow the orientations of the deep faults, the fault zones were probably more susceptible to erosion – especially by the meltwater during the glaciations.

The geological event chronology provides a possible explanation for the formation and the spatial distribution of the sediments in the LOOP 2 area. Especially the near-surface sediments are subject to high interest in the MapField Project, because of the varying Nitrate reduction capacity. The mapping shows that it is likely that reactivations of deep faults caused by loading and unloading of the ice-sheets have resulted in depressions where organic-rich sediments have been deposited in lakes and bogs. These sediments have a high potential for Nitrate reduction, and therefore local links between fault reactivation and groundwater vulnerability can be pointed out.

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