DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2021/36**

Geological mapping in MapField LOOP-areas and demo sites

Peter B. E. Sandersen & Anders Juhl Kallesøe

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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1. Foreword

This report is made in the context of the MapField project (www.mapfield.dk) in which scientists, companies, authorities, and the agriculture sector collaborate to develop environmental technologies and methods to be used in targeted nitrogen (N) regulation of agriculture. The vision is to generate crucial knowledge for protecting the groundwater, streams, and fjords from nitrogen pollution, while at the same time creating better production conditions for agriculture. MapField focuses on the upper parts of the subsurface. In MapField, precise calculations of water flow, nitrogen pathways, and the N-turnover from the individual field to groundwater and streams is required, and therefore it is important to obtain a high level of detail in all parts of the project. The MapField project is highly interdisciplinary and brings together researchers working in areas of geophysics, geology, hydrology, geochemistry, agriculture, and commercial development.

The aim of the MapField project is to produce a concept for mapping and modelling water flow paths and the fate of nitrate from the soil to groundwater, and streams. The final MapField concept will be a composite of different parts covering several scientific fields, all contributing to the common workflow and final output. An important feature of the MapField concept is that it should be versatile and cost-efficient, and therefore an objective is to build the workflow in well-defined parts with precise descriptions that can be used by future contractors This also involves the use of automatic or semi-automatic procedures and area-specific assessments selecting only the necessary parts of the developed concept needed in each case.

This report covers the geological interpretations at four selected Land Surveillance areas (LOOP areas) and a combined interpretation of the two MapField demo sites located in Salling. All locations are shown on Figure 1.1. The geological interpretations comprise new data collected in the MapField project and the existing data from the national geophysical database Gerda and the national borehole database Jupiter (www.geus.dk). The geological interpretations are a part of the MapField workflow developed at GEUS intended as a basis input for further modelling within the project.

In this report we use the concept of 'Geological Elements' (GE's). We define GE's as separate volumes of the subsurface representing groups of layers that can be related to specific parts of the geological history and therefore having separate formation histories. The delineation of the subsurface into separate GE's have the advantage that it is only necessary to model the upper and the lower boundaries of a GE consisting of multiple individual layers.
The approach is a further elaboration of concepts described in e.g. He et al. (2015), Jørgensen et al. (2015) and Høyer et al. (2015). When using the GE approach, focus is on mapping larger, discrete lithological volumes that can be related to distinct parts of the geological history of a given area.

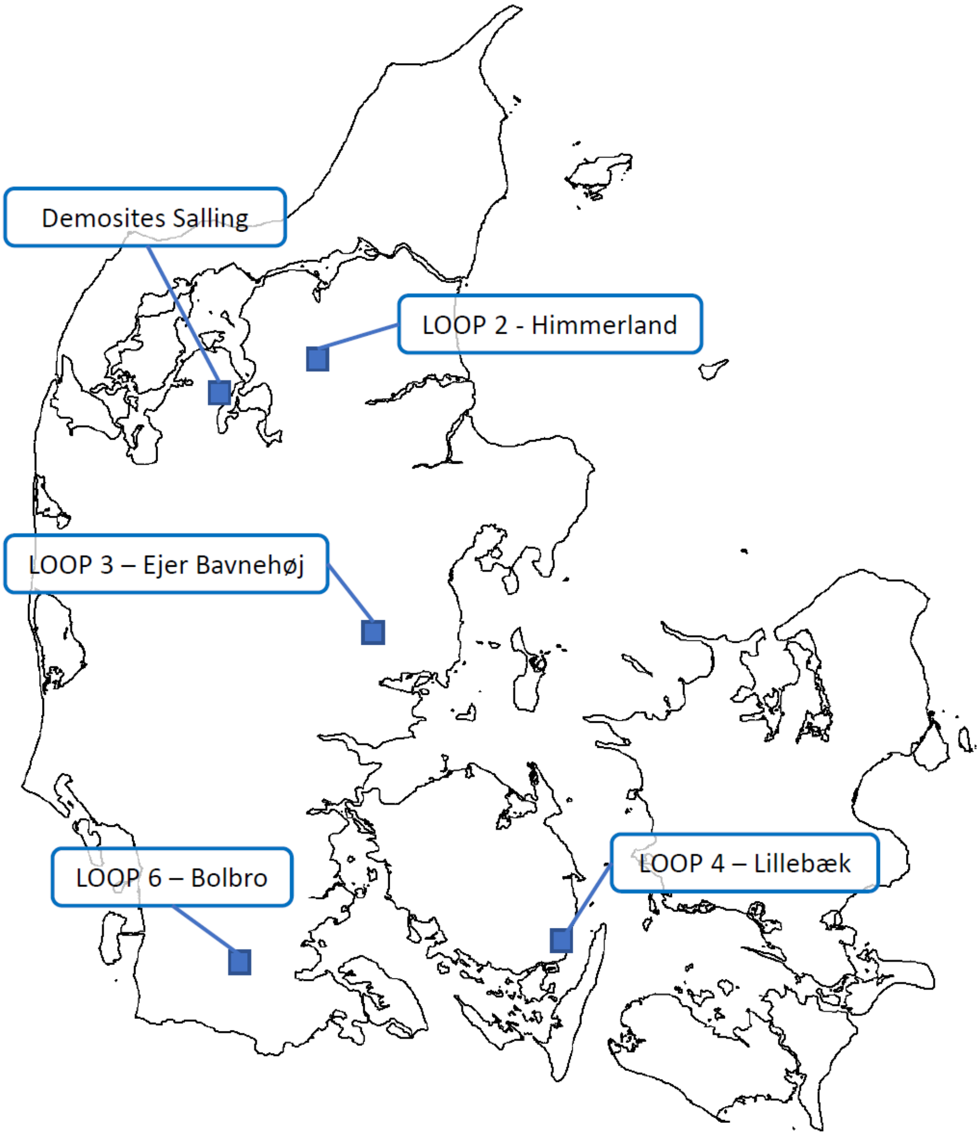


Figure 1.1: LOOP areas and demo sites selected in MapField.

2. LOOP 2 Himmerland

2.1 Geomorphology and surface geology

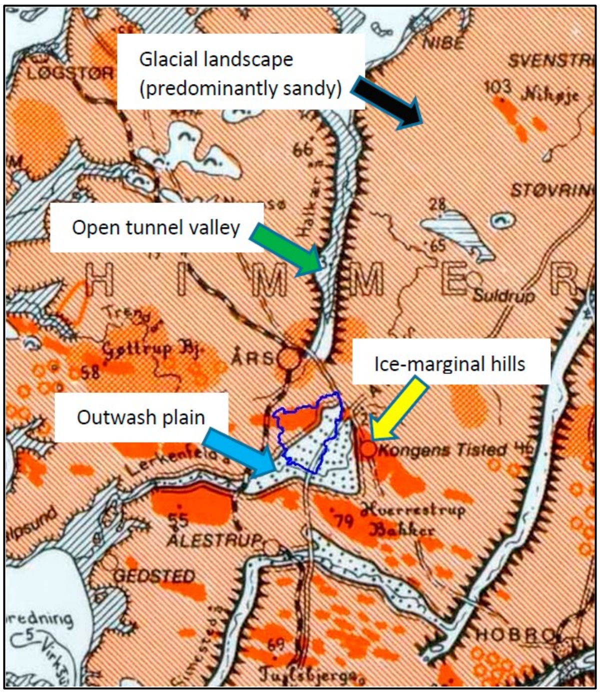


Figure 2.1: Geomorphological map. Blue polygon marks study area. Map width is approx. 35 km. (Map from Smed, 1979).

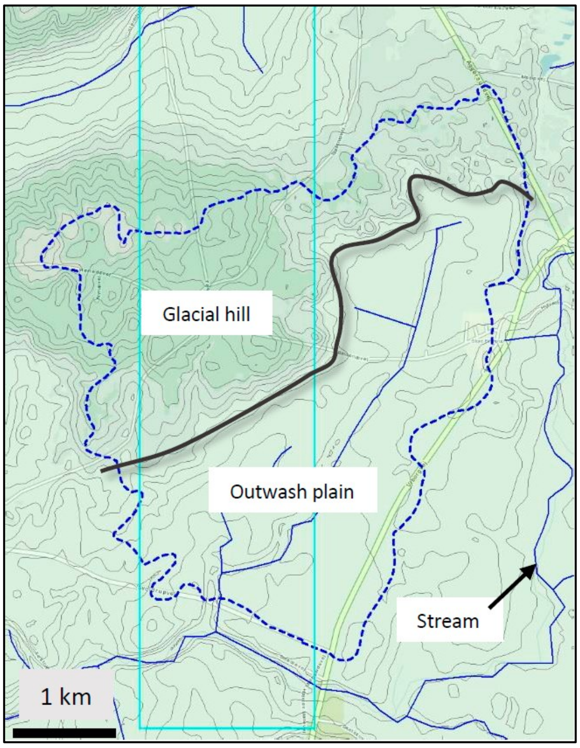
The Himmerland LOOP 2 study area (Figure 1.1 and Figure 2.1) is located in a glacial landscape in northern Jutland just south of the city of Aars. The glacial terrain is predominantly sandy and characterized by presence of prominent open tunnel valleys, outwash plains and ice-marginal hills. The study area is located partly in the hilly glacial terrain and partly on a small outwash plain from the last ice age (the Weichselian). The outwash plain is surrounded by ice-marginal hills with orientations between W-E and NW-SE (Figure 2.1).

The hilly north-western part of the study area reaches up to a little less than 60 m a.s.l. whereas the lower-lying outwash plain to the south-east slopes in a south-westerly direction from around 25 to 17 m a.s.l. (Figure 2.2). Streams on the outwash plain generally drains in the same direction.

The surface geology in the uppermost meter of the study area are dominated by meltwater sand (red colours on Figure 2.3). However, the sand can be split into meltwater sand laid down on the outwash plain and meltwater sand in the hills related to earlier ice advances/ice margins. The grey line on Figure 2.3 marks the boundary between the two sand types that have not been separated in the soil type map. Patches of clay tills and sandy tills can be found (brown colours) both on the outwash plain and in the hills to the north. Occurrences of postglacial freshwater deposits are seen in the low-lying areas (green colours).

According to Larsen et al. (2009), the latest ice-advances that reached the area in the last ice age was the ‘Kattegat advance’ from the north (29-27.000 years ago; Figure 2.4A), the ‘Main ice advance’ from northeast (23-21.000 years ago; Figure 2.4B), and finally an easterly re-advance (C: 19.000 years ago; Figure 2.4C). These ice advances are most likely responsible for many 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 was formed between the ice-marginal hills west of the ice margin of the last re-advance. The occurrences of tills among the outwash plain sediments

(Figure 2.4 and e.g. borehole DGU no. 40. 1753) constitute high-lying remnants of older glacial deposits.



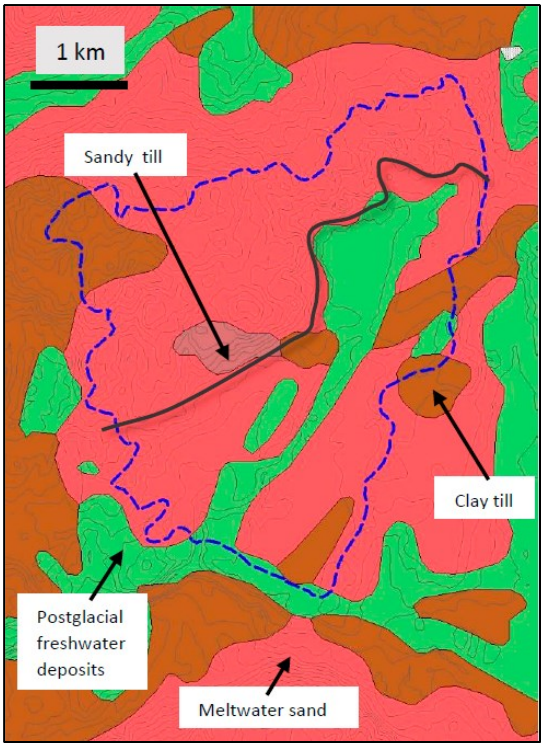


Figure 2.2 (left): Main geomorphologic elements shown with elevation model (2½ m equidistance; light green: lowest elevations; darker green: highest).

Figure 2.3 (right): Surface geology (the uppermost meter; Jakobsen & Tougaard, 2020). Grey line marks the boundary between the glacial hills and the outwash plain (see Figure 2.1).

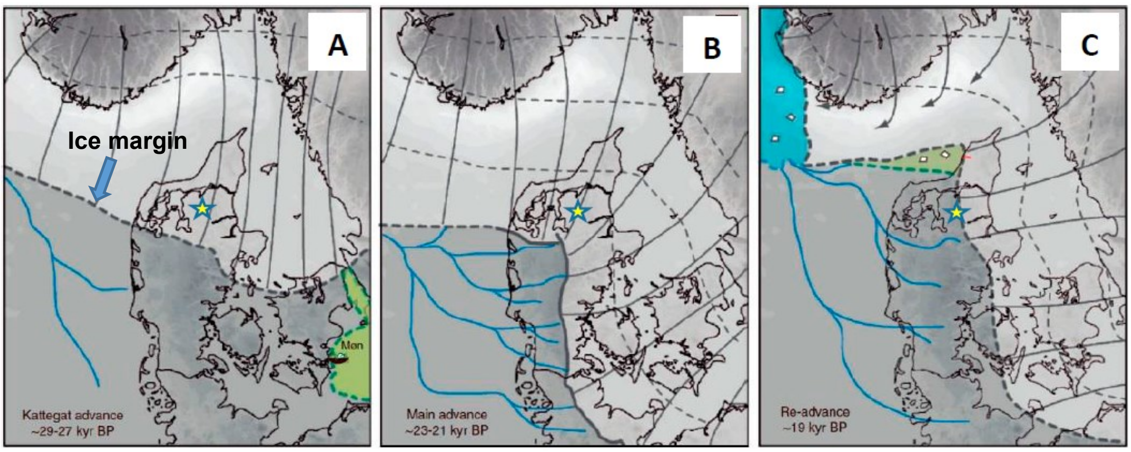


Figure 2.4: Ice-marginal positions: A) The Kattegat advance, B) The Main advance and C) Re-advance during the general recession of the Main advance. The study area is marked with yellow star. Maps from Larsen et al. (2009).

2.2 Geophysical data and boreholes

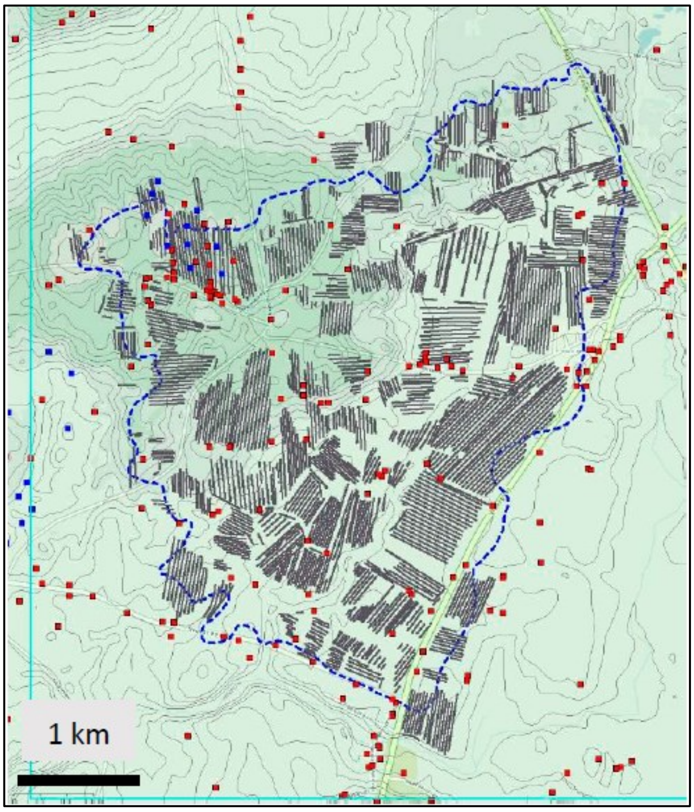


Figure 2.5: Geophysical data and boreholes. TEM data is from the Gerda database and borehole data from the Jupiter database (www.geus.dk).

Five types of geophysical data have been collected in and just around the study area (Figure 2.5):

New data collected in MapField:
- tow-TEM data (tTEM; grey lines, 456 line km) (Aarhus University 2019a)

Existing data:
- TEM data (Transient Electro Magnetic method; blue dots)
- Schlumberger soundings (a limited number in the NW part; not shown on Figure 2.5)
- Paces lines (Pulled Array Continuous Electrical Soundings; a limited number in the NW part; not shown on Figure 2.5)
- EM-data collected on one field to the north-east (not included because of limited size)

The geological data comprise boreholes from the Jupiter database (red dots).

2.3 Stratigraphy from boreholes

The oldest parts of the sedimentary succession found in borehole data within the study area, consist of light olive grey, sticky marine clay from the Eocene (e.g. borehole DGU no. 40.1006). Above, layers of dark greenish-grey, glauconitic mica clay of presumably Oligocene age have been found (e.g. borehole DGU no. 40.1006). In total, only 14 m of this pre-

Quaternary succession has been penetrated. Judged from the borehole data alone, the topography of the pre-Quaternary surface in the study area varies from -25 m a.s.l. to deeper than -83 m a.s.l.

The Quaternary succession above consists of meltwater sand and gravel, tills and meltwater clay. Gyttja and peat of up to around 5 meters thickness can be found in boreholes in the lowest parts of the terrain. Isolated rafts of pre-Quaternary sediments occur within the Quaternary succession pointing to glaciotectonic deformation (e.g. borehole DGU no. 40.1414). Most of the 78 boreholes with lithological information are less than 30 m deep and only around 8 boreholes exceed 50 m. In one borehole, the thickness of the Quaternary succession exceeds 126 m (borehole DGU no. 40.1022).

2.4 Buried tunnel valleys

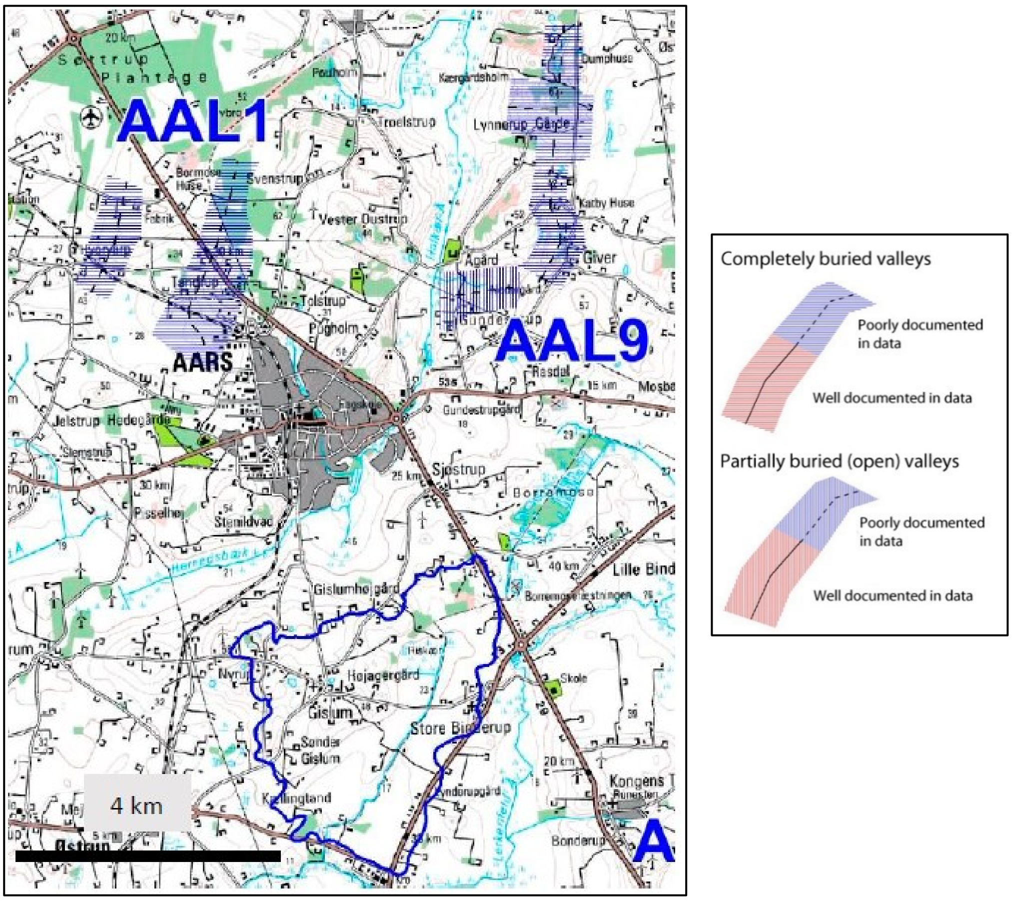


Figure 2.6: Mapped buried valleys north of the study area. Legend for the map is shown above; "AAL1" refers to locality numbers used in Sandersen & Jørgensen (2016) and on www.buried-valleys.dk.

Figure 2.6 shows the buried valleys that have been mapped just north of the study area. The valleys were generally formed as tunnel valleys by meltwater underneath the ice sheets (Sandersen & Jørgensen, 2016). The valleys around Aars are between ½ and 1 km wide and have depths of up to around 100 m. Apart from one buried valley with a WSW-ENE orientation the valleys have orientations around N-S. These orientations also characterise the valleys in the present-day terrain (see Figure 2.1). The mapped valleys may represent several generations, but the two orientations match well the orientations of the youngest ice-advances mentioned earlier.

2.5 Geological interpretation of geophysical data

The good tTEM data coverage and the nearly seven boreholes per square kilometre gives a good picture of the geological setting. Only a few older TEM soundings to the north-west lie within the study area. Older PACES and Schlumberger soundings have not been used, because of their age and because they lie inside the tTEM mapped area.

The location of six profiles through the tTEM data and boreholes (Figure 2.12 to Figure 2.17) are shown on Figure 2.7. Figure 2.8 to Figure 2.11 show four selected 2½ m slices of tTEM mean resistivities. A thin, grey hatched line marks the boundary between the glacial hill and the outwash plain.

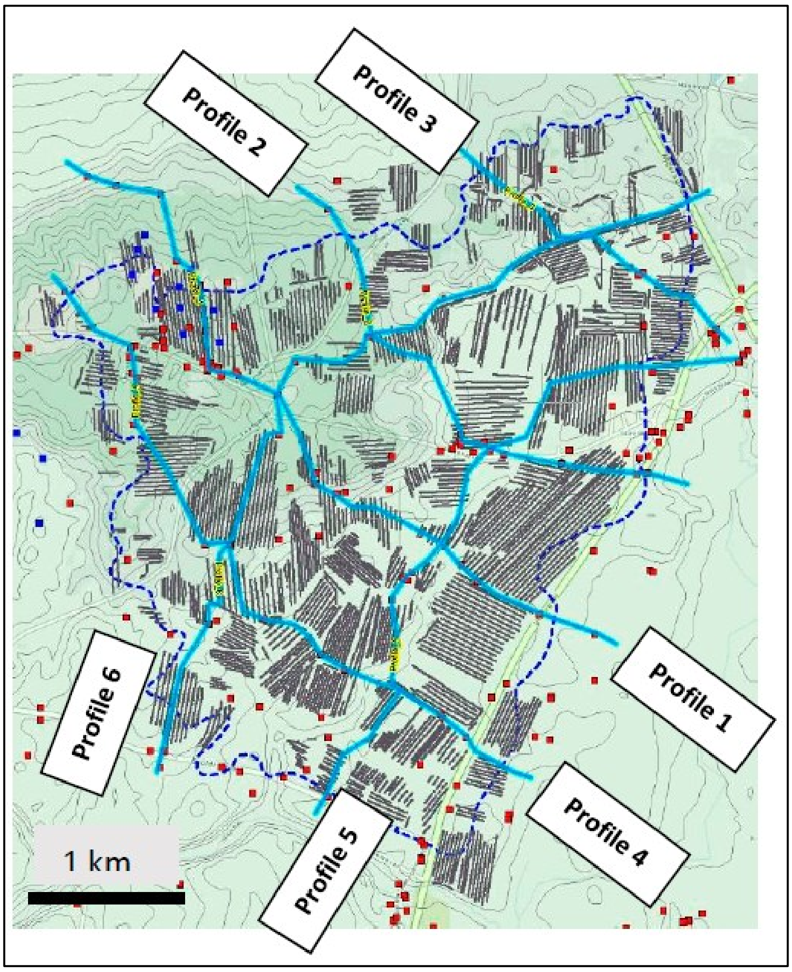
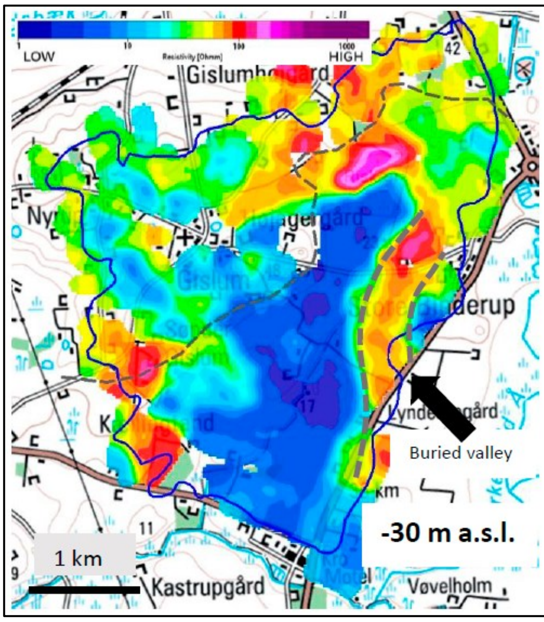


Figure 2.7: Location of selected profiles.

The deepest slice (Figure 2.8) shows that areas of very low electrical resistivity (blue colours) dominates the central and southern part of the area. The boundaries of the low-resistive layer to the north and east are rather sharp with good resistivity contrasts to the surrounding layers. Boreholes in the low-resistive layer shows that these layers are the pre-Quaternary clays mentioned earlier. To the east, a narrow N-S and around 400 m wide high-resistivity structure can be seen (black arrow). At deeper intervals, this structure becomes narrower and at -50 m a.s.l. it disappears. Upwards, it continues until 0 m a.s.l. This structure is interpreted as a buried valley eroded into the pre-Quaternary clays by meltwater below an ice sheet. To the southwest, high resistivities are also seen (Figure 2.9), but the appearance is rather patchy and the boundary to the low-resistivity area is irregular.



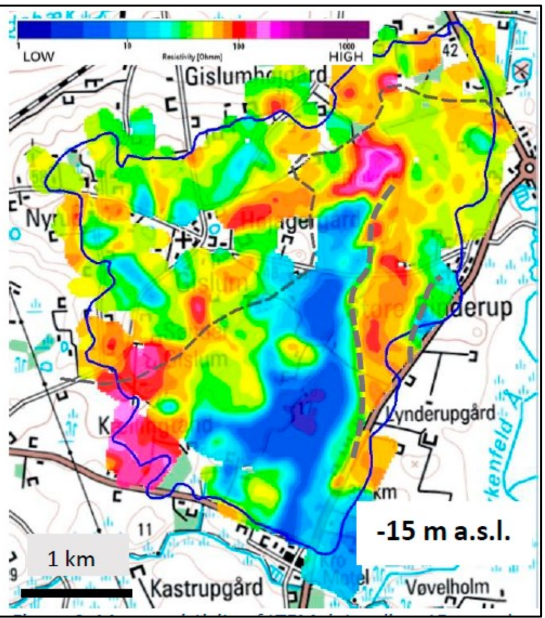
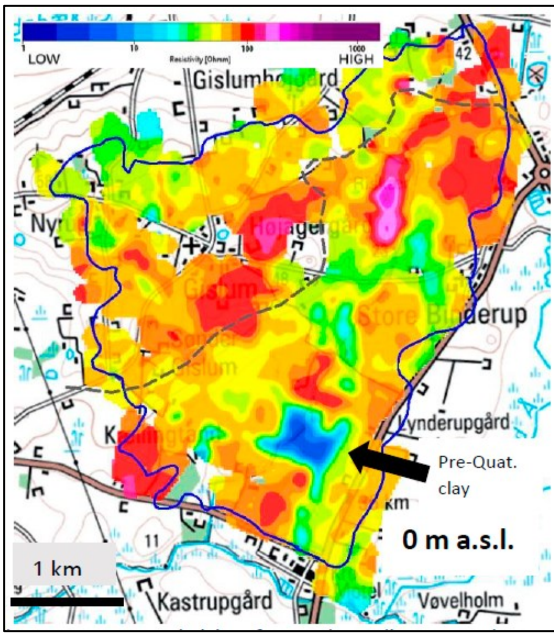


Figure 2.8 (left): Mean resistivity of tTEM data; slice -30 m a.s.l.

Figure 2.9 (right): Mean resistivity of tTEM data; slice -15 m a.s.l.



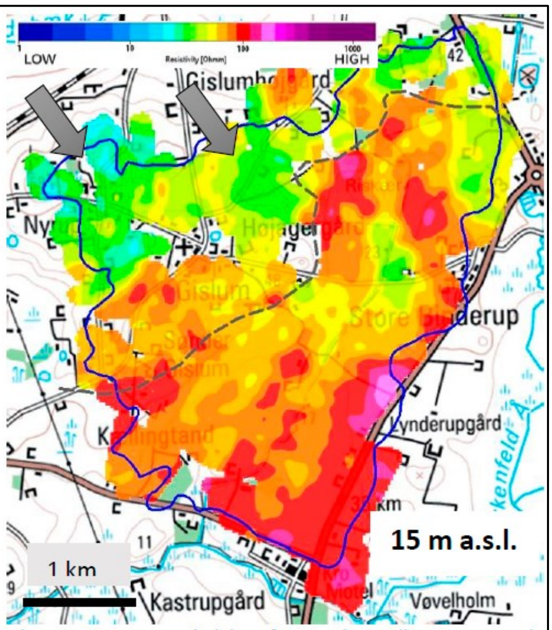


Figure 2.10 (Left): Mean resistivity of tTEM data; slice 0 m a.s.l.

Figure 2.11 (right): Mean resistivity of tTEM data; slice +15 m a.s.l.

To the north, the resistivities are very varied and show a very complicated pattern in the deep parts of the subsurface.

Above 0 m a.s.l., the very low resistivities can only be seen as a small area to the south (black arrow on Figure 2.10). Apart from this occurrence, the resistivities are generally higher, pointing to an increasing amount of sand and gravel. However, as seen on Figure 2.11, layers of moderate to low resistivities are present to the north and northwest (green to bluish colours; grey arrows). These layers are clays – either clay tills or meltwater clays. The clay is up to around 10-15 m thick and appears to cover a rather large area. At higher elevations, the succession is dominated by high resistivities representing meltwater sand and gravel. The highest resistivities are found in the unsaturated sand.

Profile 1 (Figure 2.12) crosses the area from NW to SE and shows clearly the low-resistive pre-Quaternary sediments below 0 m a.s.l. (black arrow). To the north-west, the low resistivities are not as dominant as to the southwest, and the two deep boreholes (at 1800 m) show Quaternary sediments down to around -80 m a.s.l. (DGU no. 40.918 and 40.1022). The sample descriptions show glacial sediments with a high content of pre-Quaternary material from 0 m a.s.l. and down.

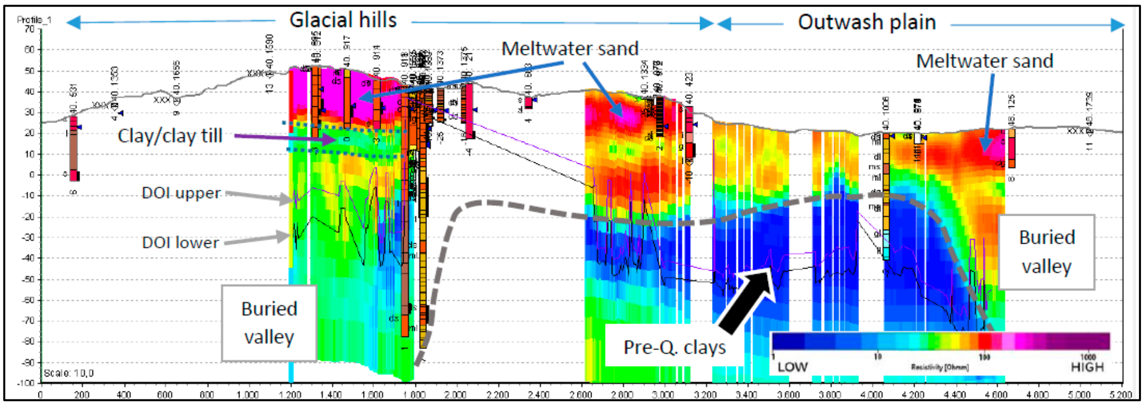


Figure 2.12: Profile 1; NW-SE. For location, see Figure 2.7. Depth of investigation (DOI) are shown with thin purple and black lines. Vertical exaggeration: 10x.

With Quaternary sediments at great depth, this most likely represent the southern flank of a deep buried valley. The infill below 0 m a.s.l. is complex and dominated by clay. To the southwest, the flank of the narrow, buried valley is marked with a black arrow on Figure 2.8. This valley has high-resistive infill and is therefore presumably dominated by meltwater sand and gravel.

To the north-west, under the hills at around 10 to 25 m a.s.l., a clay layer is found. This clay was also seen on the mean resistivity map in Figure 2.11 (grey arrows). On Profile 1, this clay layer apparently disappears or thins out underneath the outwash plain to the southeast.

Profile 2 in Figure 2.13 shows more or less the same as Profile 1, but here the clay between 10 and 20 m a.s.l. appears to continue underneath the outwash plain at a lower level, and – if the clay along the profile can be correlated – it takes a deep plunge over the buried valley to the southeast. The width of the buried valley to the northwest appears to be 1 km or more.

The clay is also seen to the left on Profile 3 (Figure 2.14), but going south-west, at 800 m, there appears to be a 25 m offset of the layers (indicated with sub-vertical, black hatched lines). All along this profile, the pre-Quaternary sequence is located very deep and way below the depth of investigation (DOI) of the geophysical measurements.

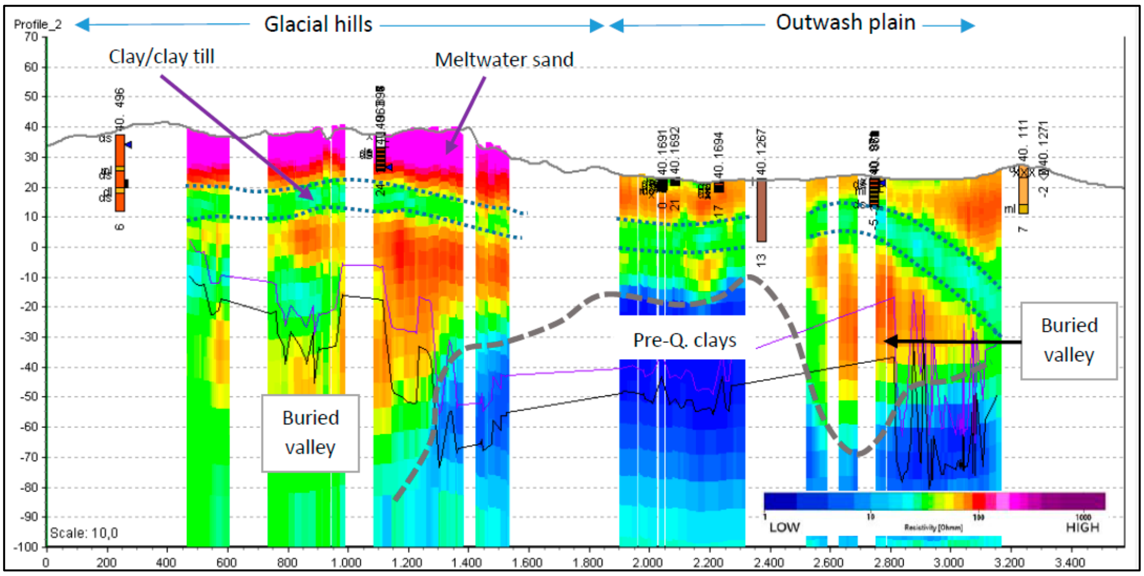


Figure 2.13: Profile 2; NW-SE. For location, see Figure 2.7. Depth of investigation (DOI) are shown with thin purple and black lines. Vertical exaggeration: 10x.

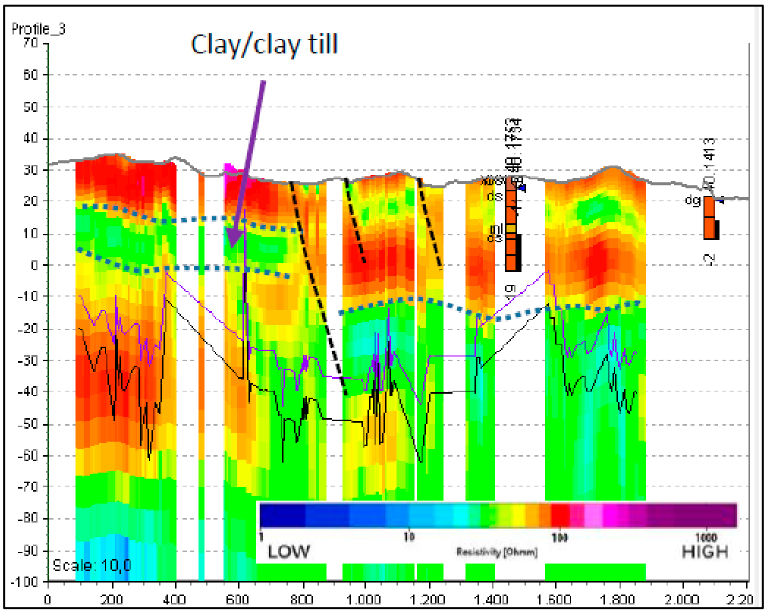


Figure 2.14: Profile 3; NW-SE. For location, see Figure 2.7. Depth of investigation (DOI) are shown with thin purple and black lines. Vertical exaggeration: 10x.

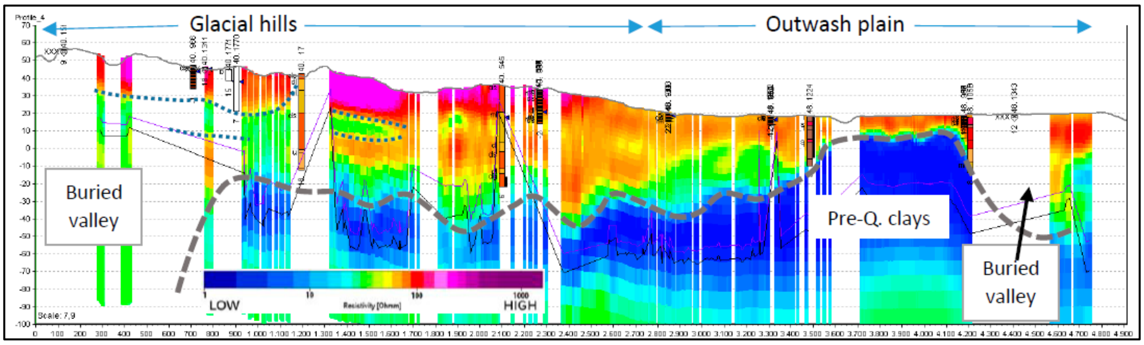


Figure 2.15: Profile 4; NW-SE. For location, see Figure 2.7. Depth of investigation (DOI) are shown with thin purple and black lines. Vertical exaggeration: c. 8x.

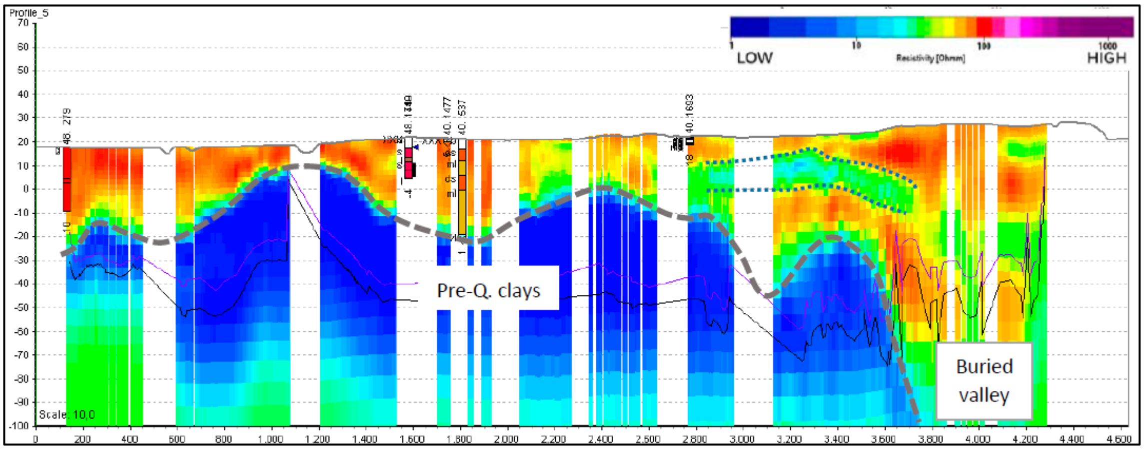


Figure 2.16: Profile 5; SW-NE. For location, see Figure 2.7. Depth of investigation (DOI) are shown with thin purple and black lines. Vertical exaggeration: 10x.

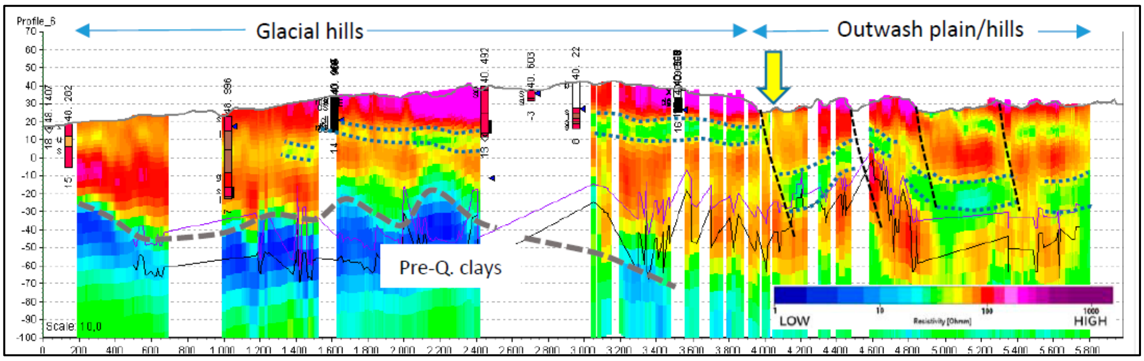


Figure 2.17: Profile 6; SW-NE. For location, see Figure 2.7. Vertical exaggeration: 10x. Yellow arrow points to an area of the outwash plain where gyttja and peat have been found in near-surface layers.

Profile 4 is reaching across the southern part of the study area and it shows the pre-Quaternary clays along all of the profile except for the north-westernmost part, where the buried valley is deeply eroded. The pre-Quaternary clays form a small plateau to the southwest (between 3500 and 4200 m) – the same which is seen in the lower central part of Figure 2.13. Just to the right of this on the profile, is the narrow, buried valley. Between the other buried valley to the northwest and the clay plateau to the southeast, there is a “basin” that seems to be eroded into the pre-Quaternary clay (seen as moderate to high resistivities to the southwest on Figure 2.9). Apparently, the clay layer in the upper part of the Quaternary succession is not present underneath the outwash plain, or maybe it is situated deeper in the succession forming the moderate resistive layer just above the Pre-Quaternary low-resistive clays (Figure 2.15 between 2800 and 3400 m). Sand between the two types of clay as is seen elsewhere, would not be resolved along this profile.

On Profile 5 (Figure 2.16), both the undulating surface of the pre-Quaternary clay and the narrow valley eroded into it can clearly be seen. However, the Quaternary clay layer in the upper part of the sequence cannot be correlated across the profile.

Profile 6 in Figure 2.17 crosses the glacial hills from southwest and to northeast across the outwash plain and the low hills just north of the plain. The Quaternary succession is dominated by high-resistive sediments, but in the upper parts of the hills, the resistivity is very high. This is most likely because the sand is unsaturated, which is backed up by water levels measured in boreholes (tiny black triangles on Figure 2.17). Within the succession under the glacial hills there is a Quaternary clay layer. However, going to the northeast, the clay layer seems to be offset around 25 m right at the boundary between the hills and the plain.

A similar observation could be made on Profile 3 (Figure 2.14). Inferred faults have been sketched on Figure 2.17 as sub-vertical black hatched lines. Interestingly, there is a nice correlation with the topography, indicating that the possible offset along the inferred faults happened at a time after the formation of the outwash plain. Tectonic disturbances of a presumably similar kind have been described from other outwash plains in Denmark (Lykke-Andersen et al., 1996; Sandersen & Jørgensen, 2015). Extensive occurrences of peat and gyttja of up to 5 meters thickness are found on the part of the outwash plain bordering the hills where the inferred offset is largest (yellow arrow on Figure 2.17).

2.6 Characterizing geological elements

To summarize the interpretations, the geological elements characterizing the LOOP 2 area have been outlined. The delineated elements are sketched in Figure 2.18 and Figure 2.19 and comprise the following:

- **GE1: Pre-Quaternary clays** (Paleogene marine clays).
- **GE2: A Quaternary sequence** consisting of a) a lower part representing the infill of incised buried valleys (the valleys are expected to penetrate the pre-Quaternary clays and reach the limestone/chalk in the deepest parts – estimated below -90 m), b) an upper part consisting of clay and sand deposits defined by a top clay layer. The layers have been glaciotectonically deformed and possibly affected by neotectonics.
- **GE3: Quaternary sand in glacial hills.** An upper Quaternary sequence in the glacial hills consisting of primarily meltwater sands from an older outwash plain and secondarily of sandy tills.
- **GE4: Weichselian outwash plain sand and postglacial sediments.** The outwash sands are generally just a few meters thick (up to 10 m). In the lowest parts of the outwash plain, postglacial organic rich deposits are overlying the sandy outwash plain sediments.

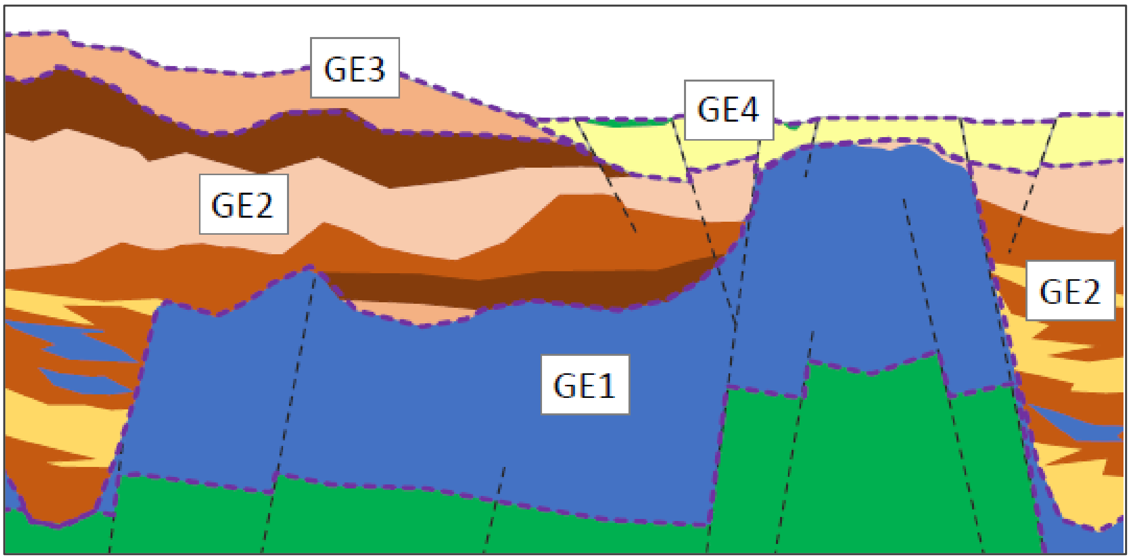


Figure 2.18: Sketch of Geological Elements in LOOP 2. From Sandersen & Kallesøe (2021).

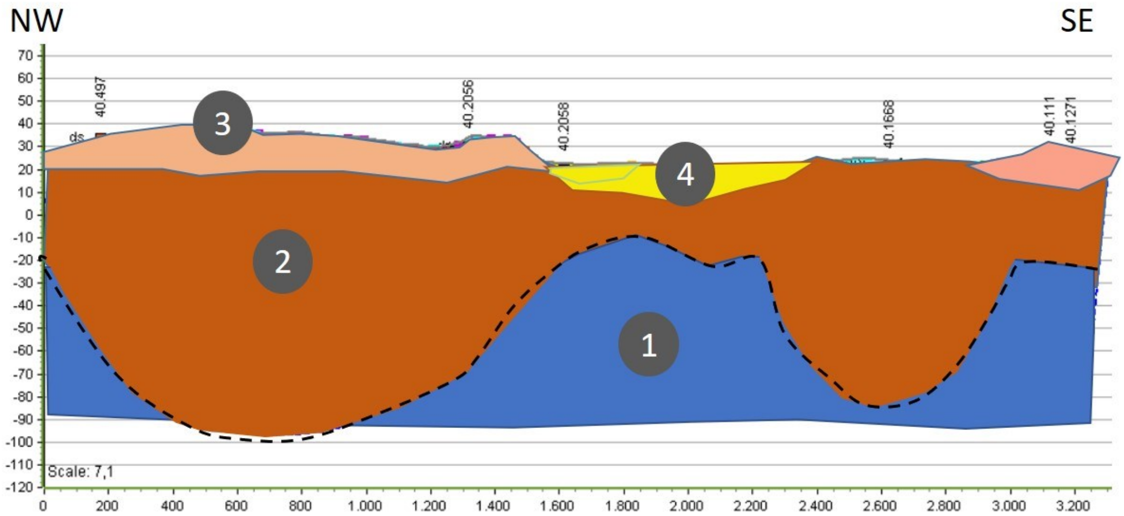


Figure 2.19: A sketch of the delineated geological elements on a NW-SE cross-section through the geological model of the LOOP 2 area.

The delineation of the geological elements in LOOP 2 is not straightforward. A number of geological events are responsible for the present architecture and character of the subsurface, such as ice advances from different directions and presumably also tectonic events which have influenced the sediments all the way to the terrain surface.

2.7 Summary and conclusions

- **Geophysical mapping:** The area has a good coverage with tTEM data. The tTEM data has a high quality and it has significantly added to the understanding of the geological setting. The tTEM provides a good resolution of individual layers and the surface of the Paleogene clays, often referred to as the good conductor.

- **Borehole information:** Despite the fact that most of the boreholes are shallow, the number of boreholes with lithological descriptions is high and there is a good correspondence between the geophysical and the geological data.

- **Sedimentary succession:** Pre-Quaternary clays with a very undulating surface can be found in a large part of the study area. The clays are in certain areas deeply eroded. Above, there is a Quaternary succession consisting of tills, meltwater sands and clays, and local occurrences of postglacial freshwater deposits.

- **Glaciotectonic deformations:** The effects of glaciotectonic deformation from north-east or east as would be expected, have not been recognized with certainty within the study area. The topography of the surrounding areas shows pronounced ice-marginal hills, so at least deformations in the hilly parts would be 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.

- **Other tectonic deformation:** As shown on Profiles 3 and 6, there are signs of tectonic events of another kind than mentioned above. Deformation of the outwash plain sediments points to events happening after the outwash plain was formed and the ice had melted away. Tectonic disturbances such as these could be caused by rebound of the subsurface due to the weight-relief from the ice. This type of deformation of the sedimentary succession should be taken into consideration alongside the glaciotectonic deformations when assessing groundwater vulnerability.

- **Buried valleys:** Indications of a large, more than 1 km wide, WSW-ENE oriented buried valley is found in the north-western part of the study area. The valley is eroded deeper than -50 m a.s.l., with a very varied infill that is mostly clayey. In addition to this, a N-S oriented, 400 m wide buried valley is found to the east. The narrow valley is predominantly filled with sand and gravel and does not reach deeper than -50 m a.s.l. Apparently, the buried valleys are only found below 0 m a.s.l.

- **Geological interpretation and correlation:** The geological interpretations of the data have added significant new knowledge to the geological understanding of the area. Despite a very complex setting in parts of the area a good co-interpretation of geological, geophysical, geochemical and geomorphological data has been possible. However, because of the few deep boreholes within the study area and the limited penetration depth of the tTEM, the geology below -50 m a.s.l. remains largely unknown and further interpretations will have to rely on data from outside the study area. Correlations between terrain features and subsurface structures paves the way for connecting the formation of the near-surface geology with sediments and structural features of the deeper subsurface.

The geology of the LOOP 2 area is further described in Sandersen & Kallesøe (2021).

3. LOOP 3 Ejer Bavnehøj

3.1 Geomorphology and surface geology

The Ejer Bavnehøj LOOP 3 study area (Figure 1.1) is located in a hilly glaciated landscape in the eastern part of Jutland just east of the highest point in Denmark (Yding Skovhøj, Figure 3.1, left). The study area lies on the northeast-facing hillside (Figure 3.1, right). The terrain is predominantly clayey. To the north of the area and west of Skanderborg, a system of open tunnel valleys forms a low-lying area with several lakes (Figure 3.1, left).

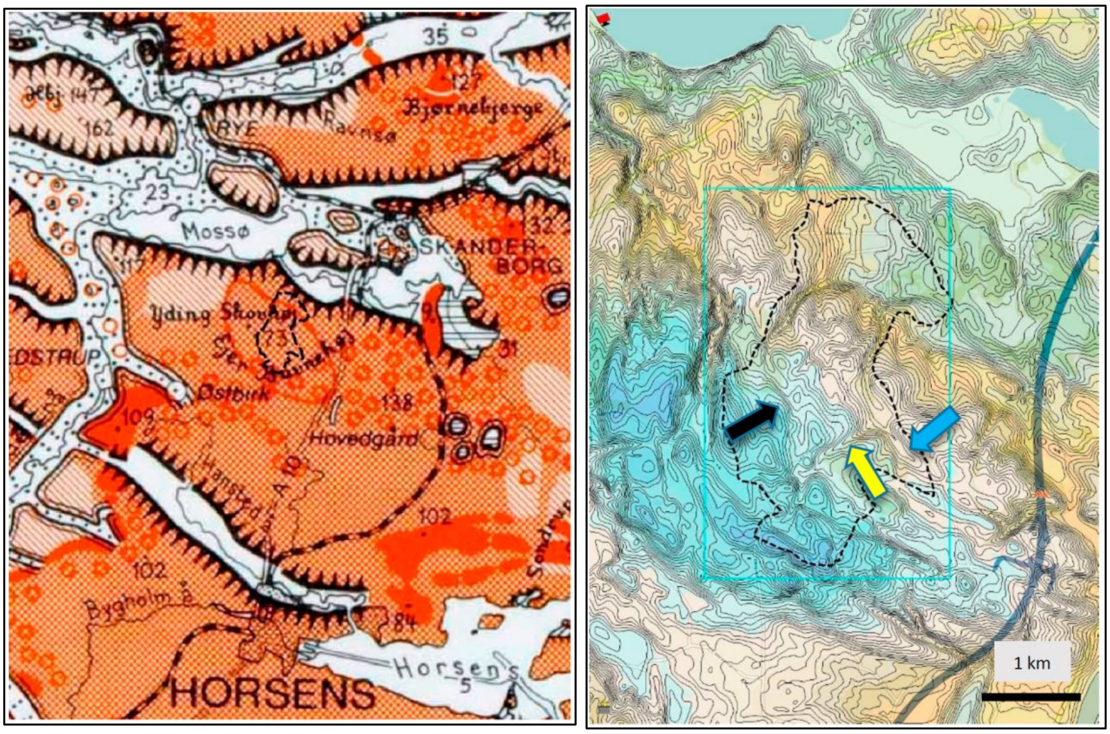


*Figure 3.1: **Left: Morphological map. Study area marked with a thin, hatched black line. Map width is approx. 28 km. (Map from Smed, 1978). Right:** Digital elevation model (2½ m equidistance; highest elevations: blue, lowest: green).*

In the southern part of the study area, the elevation reaches 170 m a.s.l. and to the northeast, it slopes down to around 40 m a.s.l. The terrain, as seen on Figure 3.1, right, is dominated by orientations perpendicular to the slope (VNV-ESE to N-S) seen as either valleys (blue arrow) or abrupt slope changes (black arrow). In a few places, erosional valleys parallel to the slope can be seen (WSW-ENE to SW-NE; yellow arrow).

A map of the surface geology in the uppermost metre is shown on Figure 3.2, left. Clay tills dominate the study area, but to the north, in the lowest parts of the terrain, occurrences of meltwater sands are found. Locally, postglacial freshwater deposits can also be found.

The two latest ice-advances that reached the area were the ‘Main ice advance’ from north-east and later on the ‘East Jutland advance’ from southeast (Larsen et al., 1979). The ice-advance from northeast had a temporary ice margin approximately at the culmination of the hills (‘C4’ on Figure 3.2; yellow arrows), whereas the ice from southeast apparently stopped just short of the study area (‘D’ on Figure 3.2, right; red arrows).

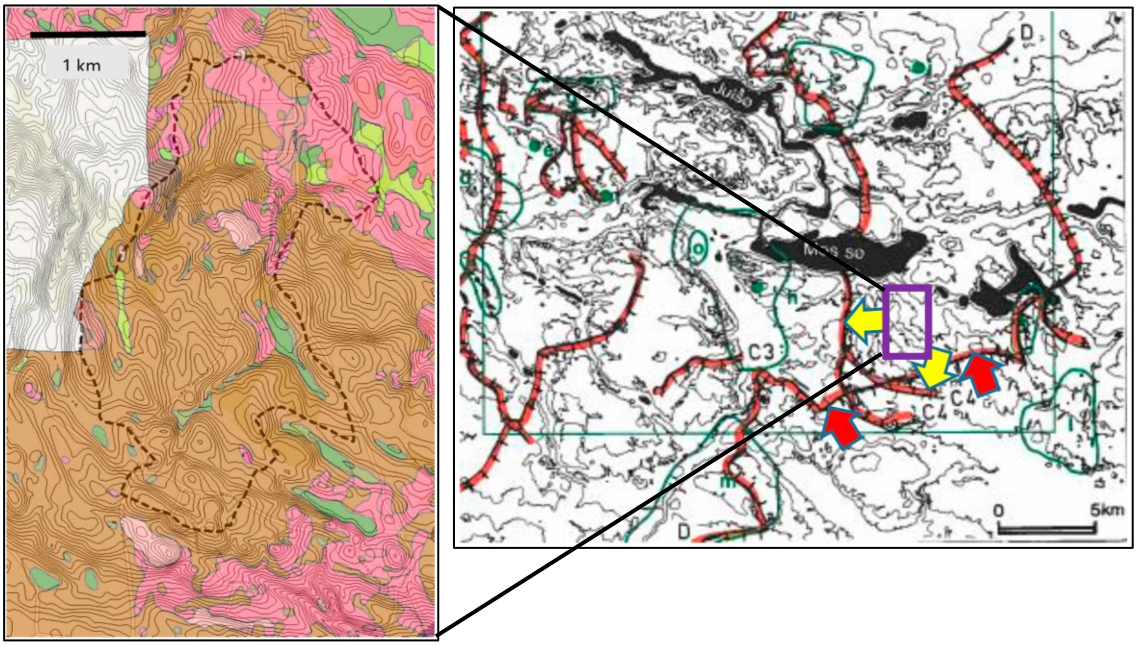


*Figure 3.2: **Left:** Surface geology (uppermost meter; Jakobsen & Tougaard, 2020). Brown colours: Tills; Red: Meltwater sand; Light red: Meltwater clay; Green: Postglacial freshwater deposits. **Right:** Ice-marginal positions (red colour). ‘C’-positions: Main advance; ‘D’-position: East Jutland advance. Study area marked with purple rectangle. Map detail from Larsen & Kronborg (1994).*

3.2 Geophysical data and boreholes

Three types of geophysical data have been collected in and just around the study area (Figure 3.3):

New data collected in MapField:

- tow-TEM data, 218 line km with a line spacing of 25 m (tTEM; grey lines; white arrow) (Aarhus University 2019b); see also Sandersen et al. 2021.

Existing data:

- MEP data (Multi Electrode Profiling or Electrical Resistivity Tomography, ERT) shown as red lines (black arrow)
- SkyTEM data (airborne Transient Electro Magnetic method) shown in blue (red arrow)
- The geological data comprise boreholes from the Jupiter database (red dots, yellow arrow)

3.3 Stratigraphy from boreholes

The oldest parts of the succession found in boreholes within the study area consist of grey to greenish sticky marine clay of Eocene age (e.g. DGU no. 98.457). Above this clay, scattered and thin occurrences of black mica clay (presumably Oligocene; e.g. DGU no. 98.80) can be found.

The Quaternary succession above consists of predominantly clayey tills, meltwater sand, meltwater gravel, and minor occurrences of meltwater clay. The thickness of the Quaternary succession varies from a few meters to more than 100 m. Isolated rafts of pre-Quaternary sediments occur occasionally within the Quaternary succession suggesting glaciotectonic deformation. Generally, the area has only a few deep boreholes, but still the lithological information from the boreholes gives a good impression of the sedimentary succession and fits well with the surface geology map (Figure 3.2). However, the freshwater sediments seen on the surface geology map have not been found in any of the boreholes.

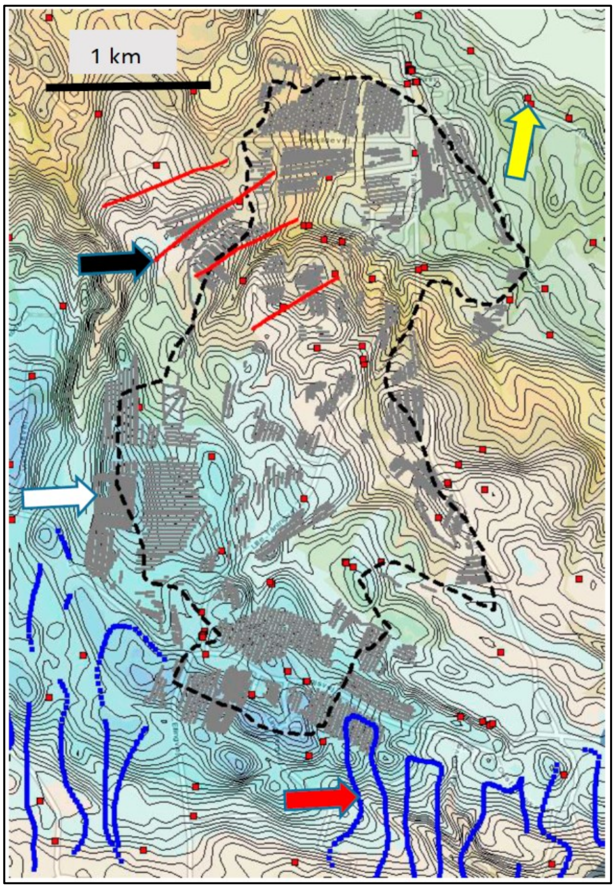
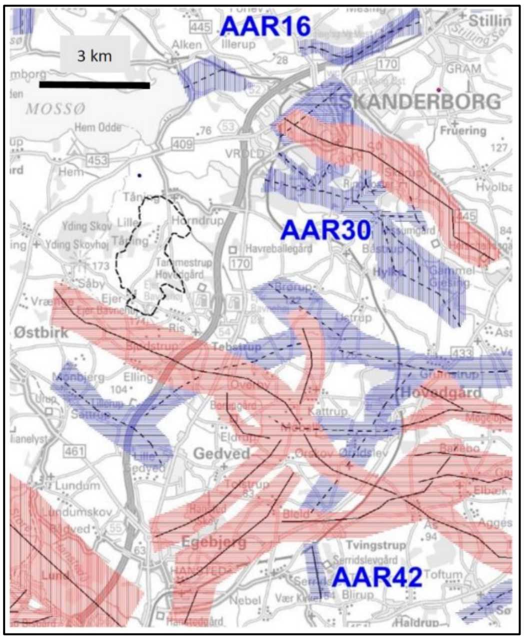


Figure 3.3: Geophysical data and boreholes. Download from Gerda and Jupiter databases (www.geus.dk).

3.4 Buried tunnel valleys

Figure 3.4 shows the buried valleys that have been mapped outside the study area. The buried valleys were formed as tunnel valleys underneath the ice sheets, they are generally between 1 and 2 km wide, and some of them show depths of more than 100 m (Sandersen & Jørgensen, 2016). As can be seen on the map, the valleys mostly have two preferred orientations, one around WNW-ESE/NW-SE and the other around SW-NE/WSW-ENE. The WNW-ESE/NW-SE orientation is also clearly seen in the present-day terrain (see Figure 3.1).

The mapped valleys most probably represent several generations, but the two mentioned orientations match fairly well the orientations of the two youngest ice-advances mentioned above. Relative age relationships of the valleys found by Sandersen & Jørgensen (2016) confirm that the WNW-ESE/NW-SE orientation is the youngest and therefore probably represents the East Jutland Advance.



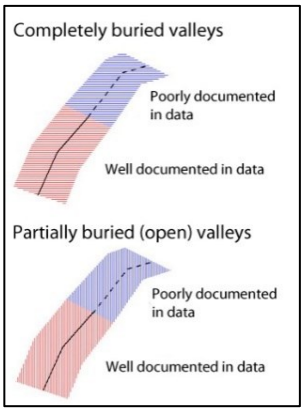


Figure 3.4: Mapped buried valleys close to the study area (shown with black hatched line). Legend for the map is shown above; "AAR30" refers to locality numbers used in Sandersen & Jørgensen (2016) and on www.buried-valleys.dk.

3.5 Geological interpretation of geophysical data

The tTEM cover is patchy and although the geology has large variations, the data gives a very good impression of the geological setting. The four MEP-profiles at the northwestern edge of the area provide valuable information and a good possibility for comparing the two methods. The SkyTEM-data is located outside the study area, but it adds valuable information on the geological connections to the neighbouring areas to the south.

Profiles through the tTEM data and boreholes are shown on Figure 3.5 and a number of these profiles are shown in the following. SkyTEM data and MEP-profiles are included on selected profiles.

Two slices of a tTEM 3D resistivity grid are shown in Figure 3.6. The left figure shows a 5-m slice 50 m a.s.l. revealing that the southern and central parts of the area have low resistivities (blue), whereas the north-eastern part of the area has moderate to high resistivities (green to red). The 85 m a.s.l. slice in the right figure shows that at higher altitudes, bands of higher resistivities emerge in the low-resistivity sediments. Generally, the tTEM data shows large variations in the elevation of the good conductor (Paleogene clays).

In Figure 3.7, MEP data and tTEM data are shown with some overlap in the left side of the profile. The two data sets show agreement on the level of resistivity and depth to the good conductor, but the tTEM reveals slightly elevated resistivities at some depth below the low resistivity layer close to the surface (see yellow arrow). Apparently, the MEP method cannot penetrate the low-resistive layer as good as the tTEM method. The resulting picture of the subsurface is a low-resistivity raft covering layers of higher resistivity (between 200 and 550 m), pointing to a deformed sedimentary succession. The mapped layers are well above the tTEM DOI shown as grey lines on the profile. The low-resistivity layer is the sticky Eocene clay found for instance in borehole DGU no. 98.457 (blue bottom layer). To the right on the MEP data, a part of a valley-infill can be seen (bottom of valley is highlighted with a black hatched line).

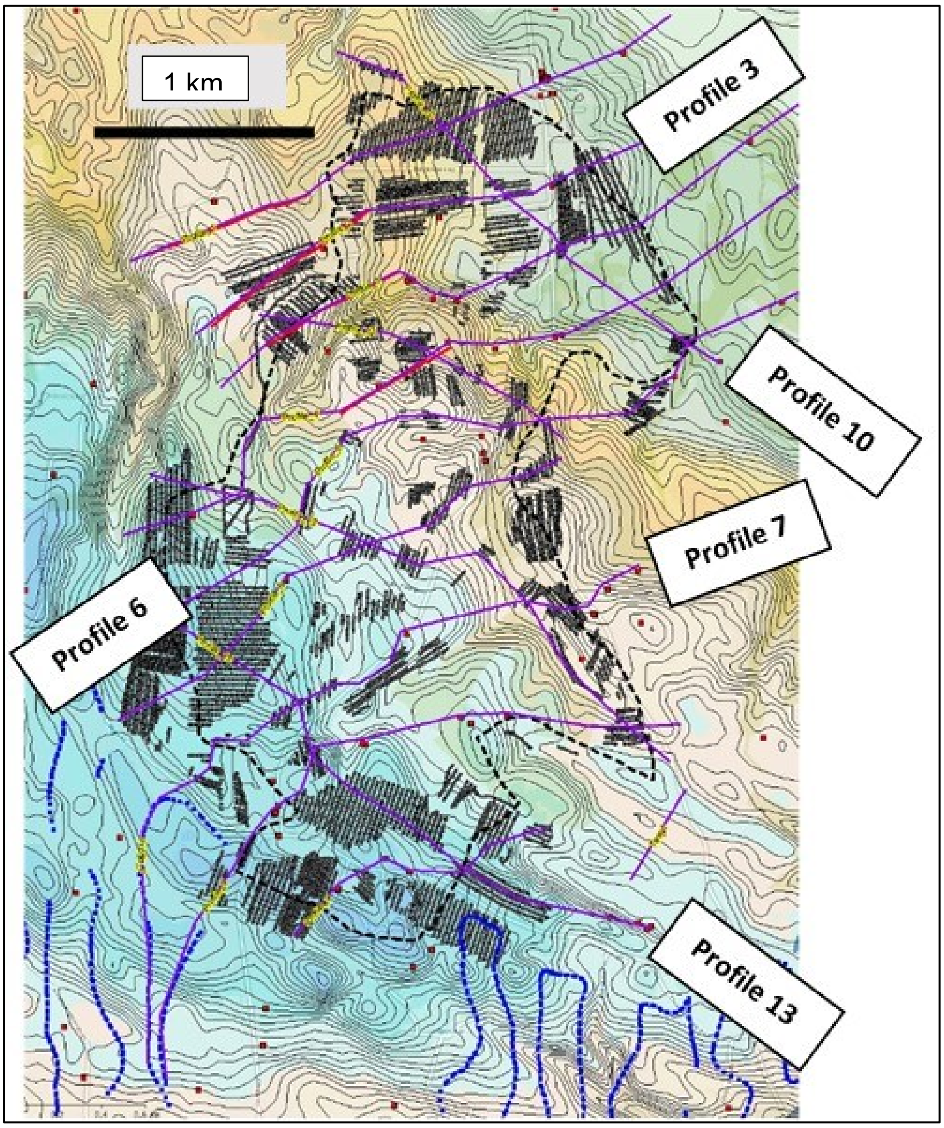


Figure 3.5: Location of selected profiles.

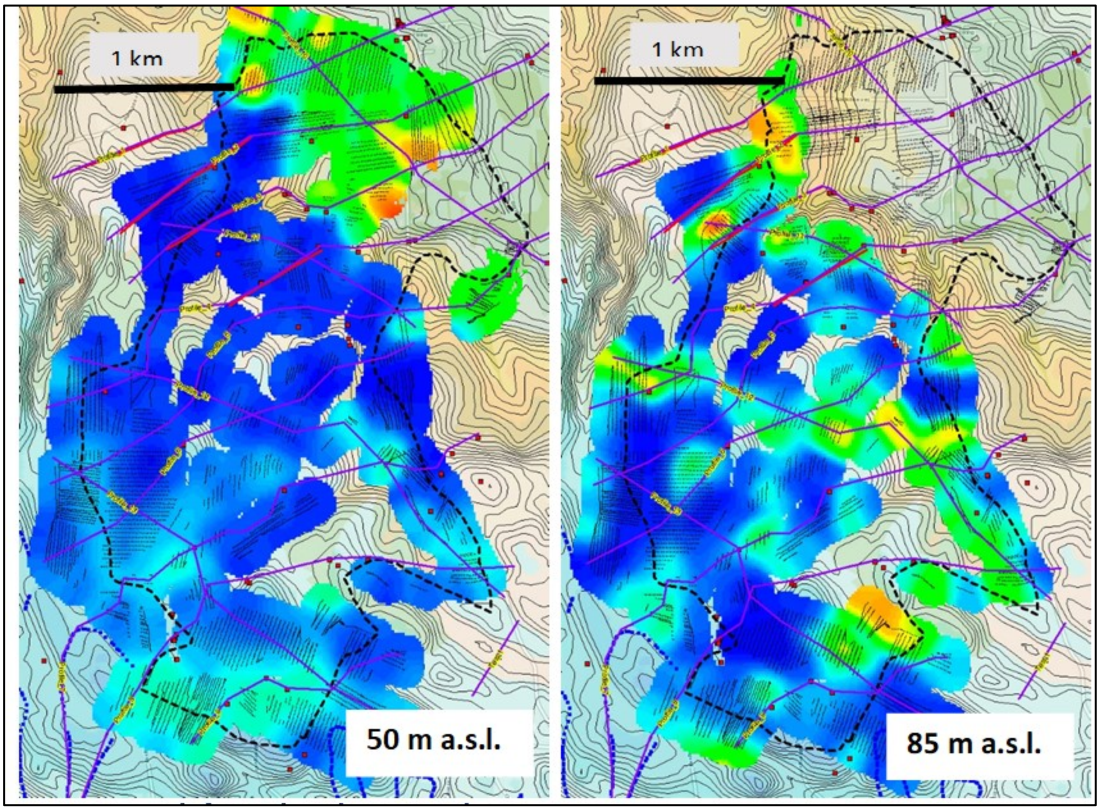


Figure 3.6: ***Left:*** *3D grid of tTEM data, slice 50 m a.s.l.* ***Right:*** *3D grid of tTEM data, slice 85 m a.s.l.*

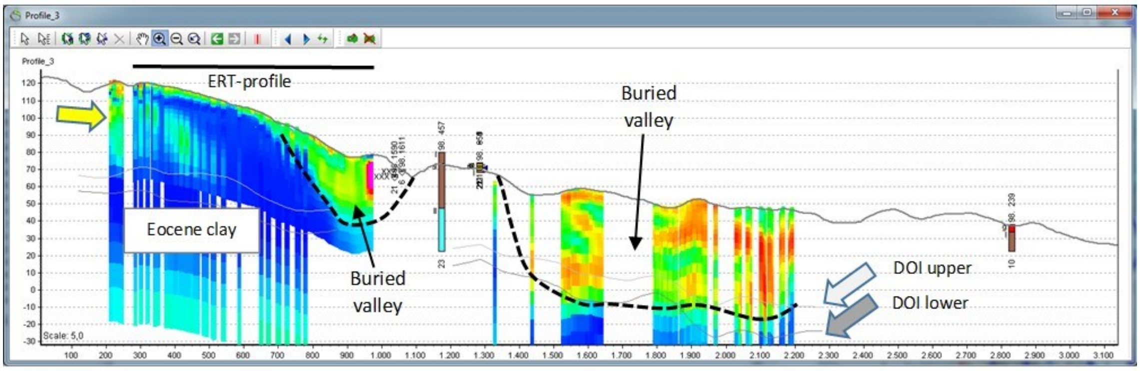


Figure 3.7: Profile 3; WSW-ENE. Thin grey lines represent upper and lower DOI of tTEM data. For location, see Figure 3.5.

The right side of the profile (Figure 3.7) shows a more than 50 m thick, complex succession of moderate to high resistivities probably consisting of tills and sandy/clayey meltwater sediments. The succession appears to be deformed. The layers occur in the northern part of the study area (Figure 3.6) and probably constitute the infill of a NW-SE oriented buried valley. A genetic relation to the valleys farther to the southeast, seen on Figure 3.4, is possible. The bottom of the valley, however, is not fully resolved by the tTEM.

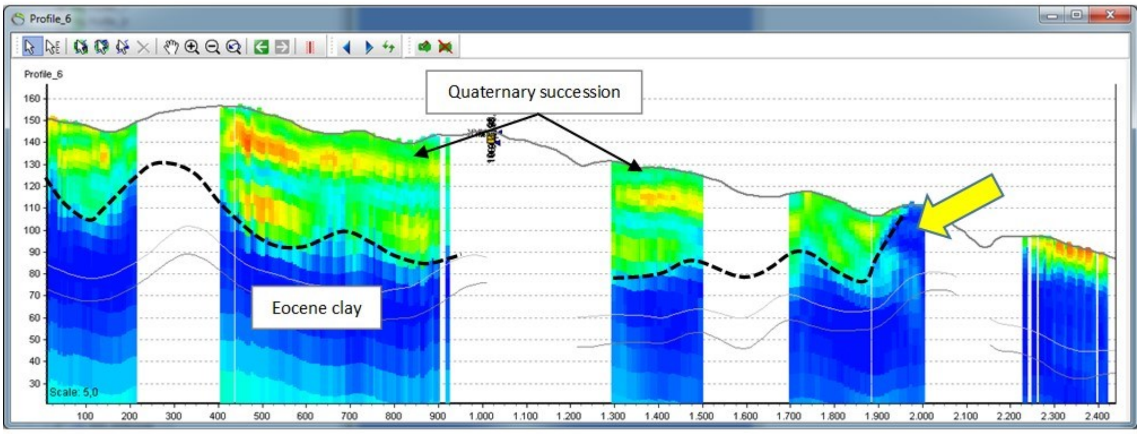


Figure 3.8: Profile 6; WSW-ENE. Thin grey lines represent upper and lower DOI of tTEM data. For location, see Figure 3.5.

The profile in Figure 3.8 crosses the high parts of the study area. The surface of the Eocene clay (blue; low resistivities) shows some variation and to the right a slab of a low-resistivity layer is seen over layers of slightly higher resistivity (yellow arrow; between 1900 and 2000 m). The layers of moderate to high resistivity (green to red) represent the Quaternary succession, and although other parts of the subsurface seem very deformed and complex, this part seems to be less deformed and fairly easy to correlate. The succession above the Eocene clay appears to consist of two high-resistivity layers each covered by a low-resistive layer.

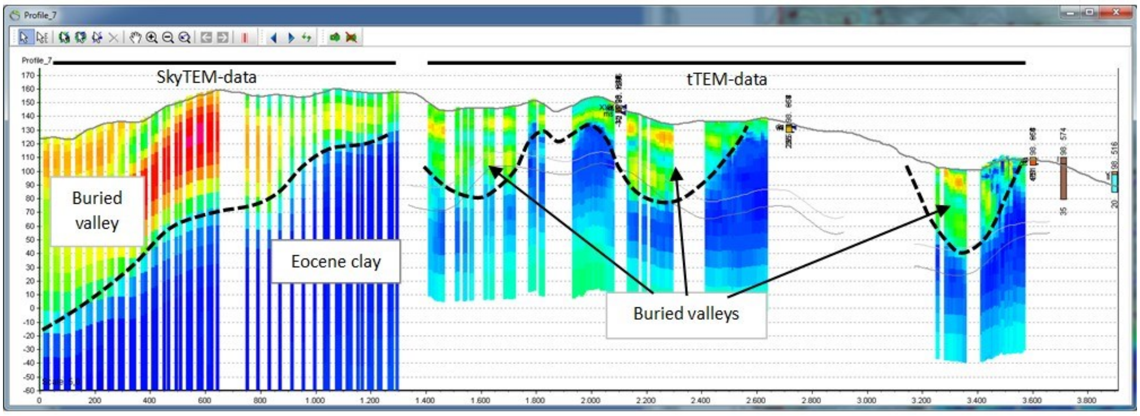


Figure 3.9: Profile 7; SW-NE. Thin grey lines represent upper and lower DOI of tTEM data. For location, see Figure 3.5.

The profile 7 in Figure 3.9 shows SkyTEM data on the left side and tTEM data on the right side. The two datasets show good correspondence despite the tTEM data does not penetrate as deep as the SkyTEM-data. To the left the SkyTEM data maps the deep buried valley shown on Figure 3.9 just south of the study area. In the middle of the profile, two smaller buried valleys are crossed at 1400-1800 m and 2100-2500 m. Apparently, the valleys have comparable infill, but there are, however, no boreholes to confirm this. To the far right, another buried valley is seen at 3200-3500 m.

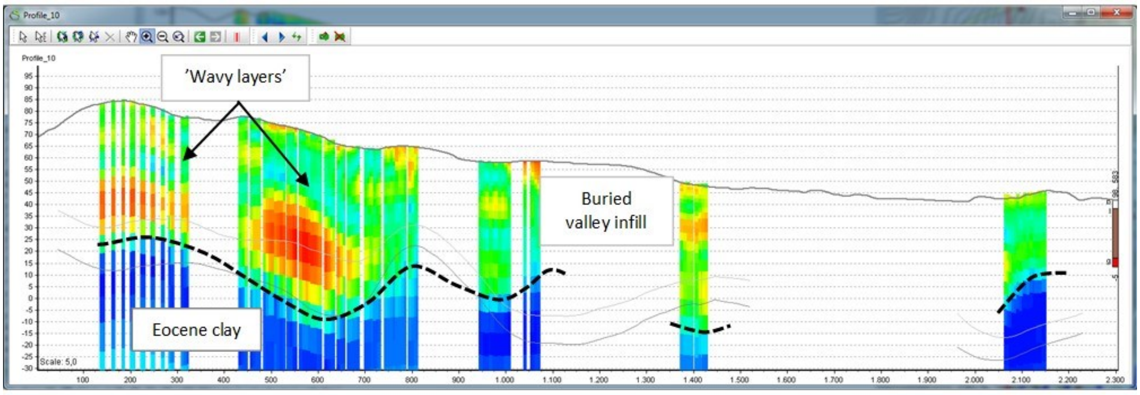


Figure 3.10: Profile 10; NW-SE. Thin grey lines represent upper and lower DOI of tTEM data. For location, see Figure 3.5.

Profile 10 in Figure 3.10 shows the infill of the broad buried valley to the northeast. Especially in the left side of the profile, the layers have a wavy appearance pointing to pronounced glaciotectonic deformation.

Profile 13, shown on Figure 3.11, gives a very clear picture of the valleys in the southernmost part of the study area, and just as it was seen on Figure 3.8 and Figure 3.9 the valley infill seems to be rather undisturbed and apparently being of more or less the same type. This succession is presumably penetrated in the borehole DGU no. 98.942 just southeast of the study area. In this borehole, layers of meltwater sand and gravel are interlayered by clay tills and meltwater clay. The meltwater clay is most likely responsible for the relatively low resistivities in the middle of the Quaternary succession mapped by the tTEM (Figure 3.11; yellow arrow).

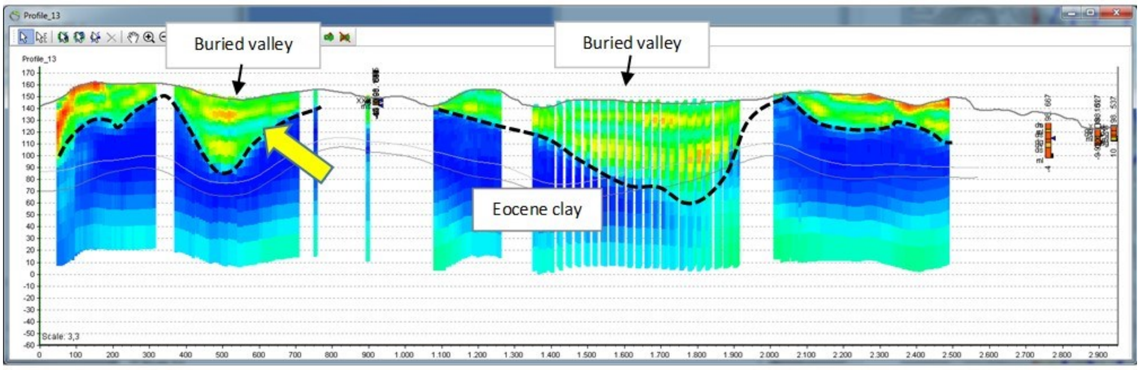


Figure 3.11 : Profile 13; NW-SE. Thin grey lines represent upper and lower DOI of tTEM data. For location, see Figure 3.5.

3.6 Characterizing geological elements

To summarize the interpretations, the geological elements characterizing the LOOP 3 area have been outlined. The delineated elements are sketched in Figure 3.12 and comprises the following:

- **GE1**: Pre-Quaternary clays
- **GE2**: Small buried valleys with infill and Quaternary 'plateau' sediments above

- **GE3**: Large buried valley with infill consisting of Quaternary meltwater sand, meltwater clay and clay till

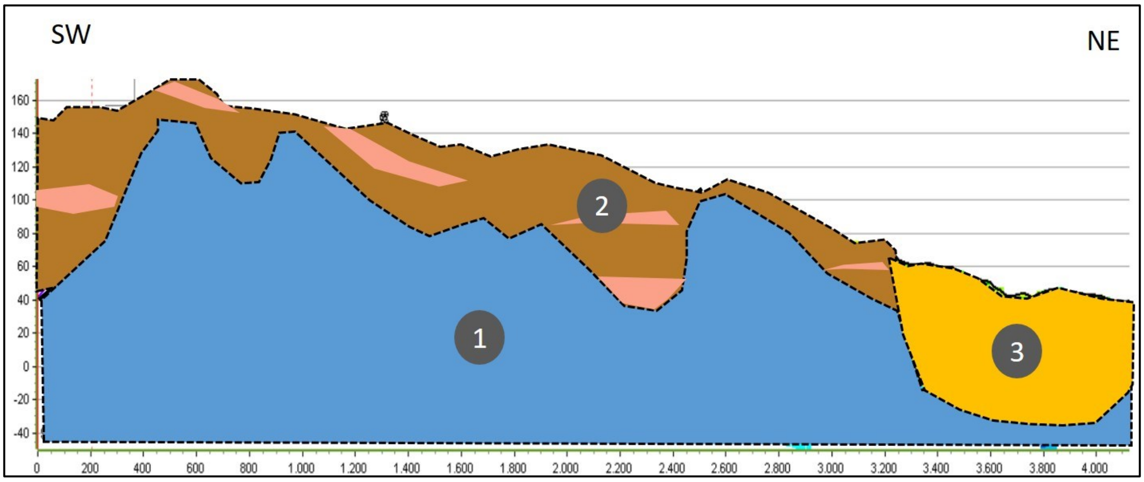


Figure 3.12: Sketch visualizing the delineated geological elements within LOOP 3.

3.7 Summary and conclusions

- **Geophysical mapping:** The area has a patchy coverage with geophysical data, but the tTEM data has greatly improved the understanding of the geological setting. The tTEM provides a good resolution of individual layers and the surface of the good conductor (Paleogene clay). In some cases, the tTEM manages to map slightly higher resistivities beneath rafts of the Paleogene clay.

- **Borehole information:** The information from boreholes is limited as many of the boreholes are shallow, but the general perception of the succession is good. The Eocene clays can be found in all of the study area showing very varied elevations; highest to the SW and lowest to the NE. Above the Eocene clay, a Quaternary succession consisting of tills, meltwater sands and clays and occasional occurrences of postglacial freshwater deposits are found. No boreholes, however, have been placed in postglacial deposits.

- **Glaciotectonic deformations:** The effects of glaciotectonic deformation from northeast can easily be seen in the terrain as pronounced orientations of hill crests, slopes, and erosional valleys. In the tTEM data, folded sedimentary successions and dislocated slabs of Eocene clay can be seen. The Main ice advance was probably responsible for the glaciotectonic deformation from the northeast, whereas the younger East Jutland advance from southeast probably did not override the study area.

- **Buried valleys:** The surrounding areas show buried valleys of varied size and with preferred orientations roughly around NW-SE and SW-NE. A large, buried valley is found to the northeast within the study area and the tTEM-data shows signs of deformations of the valley infill. In the highest parts of the study area to the southwest, narrower buried valleys are found in the Eocene clay. These valleys are presumably filled with roughly the same type of sediments and because they seem to be more or less undeformed, they are probably filled with meltwater sediments from the youngest ice advance when it resided just southeast of the study area. The valleys could be either eroded by meltwater streams or formed as longitudinal lows formed between slabs of ice-pushed sediments. If so, they are *not* formed as tunnel valleys underneath the ice.

- **Geological interpretation and correlation:** The interpretations of the data have revealed a good correlation between the terrain and the subsurface structures. These observations fit well into the current knowledge of the latest geological events in the area, thus providing good possibilities of making robust geological correlations between the geological and geophysical data.

4. LOOP 4 Lillebæk

4.1 Geomorphology and surface geology

The Lillebæk study area (Figure 1.1) is located in a glacial moraine landscape in the south-eastern part of Funen (Figure 4.1). The landscape west of the LOOP area is characterized as a dead ice landscape where also end moraine hills and kame hills can be identified. The end moraine hills approx. 3 km west of the study area indicate the limit of the last ice advance covering the area – The Belt Sea advance, 18-17 kyr BP (Houmark-Nielsen, 2005). The ice push was from a south-easterly direction. To the east, the LOOP area is located in a glacial moraine landscape that extends towards the coast.

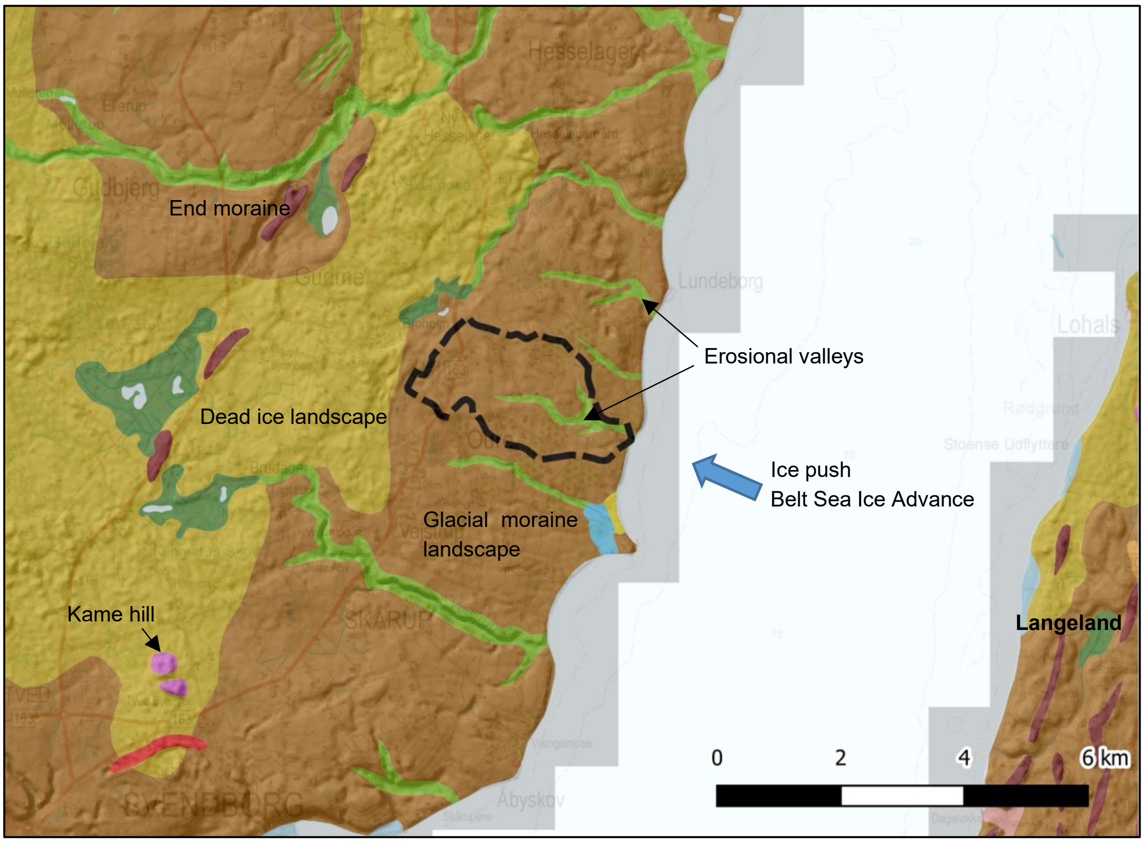


Figure 4.1: Geomorphological map (GEUS, 2018). The LOOP 4 study area is marked with a dashed black line.

The topography in the LOOP 4 area shows a general slope from the gentle glacial hills in west to the coastline to the east. The western part reaches elevations up to 60 m a.s.l. and has a thicker Quaternary sequence than the lower lying area towards the coastline. The central part of the study area is about 20-30 m a.s.l., while the erosional cliffs at the coastline to the east show elevations around 10 m a.s.l. (Figure 4.2). An erosional valley hosts the brook 'Lillebæk' (Figure 4.2).

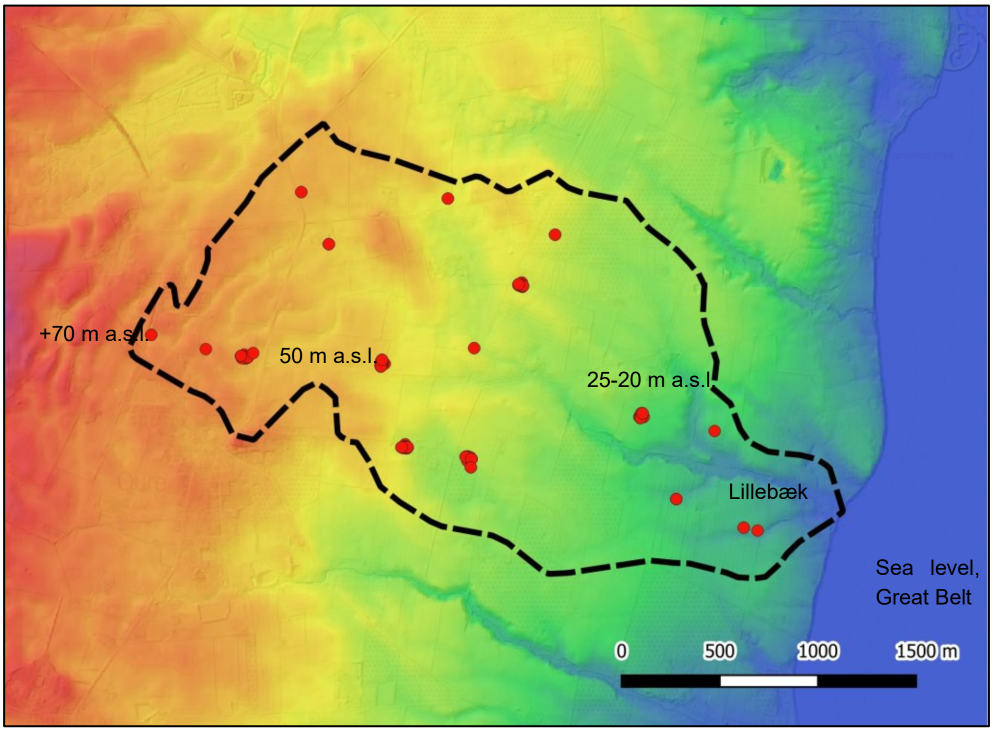


Figure 4.2: Digital elevation model (highest elevations: red, lowest: blue). Red dots represent LOOP sample stations.

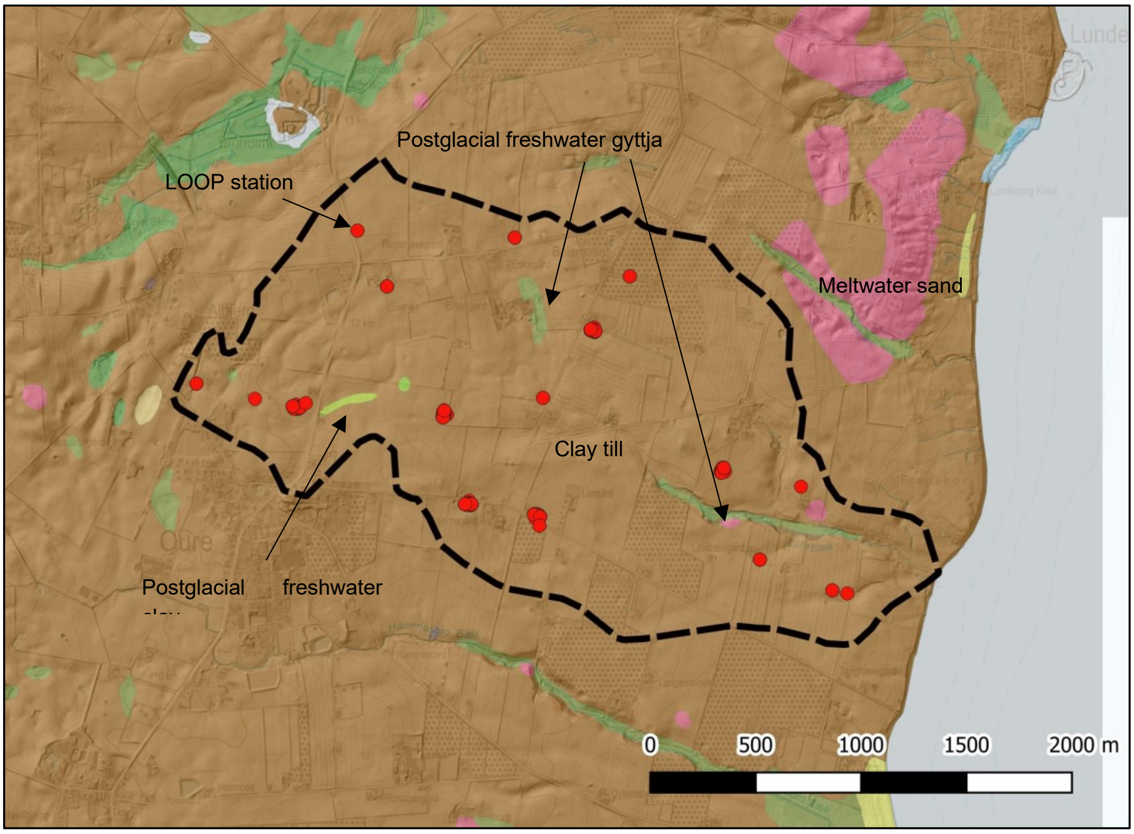


Figure 4.3: Surface geology (the uppermost meter; Jakobsen & Tougaard, 2020). Brown colours: Tills; Red: Meltwater sand; Green: Postglacial freshwater deposits (gyttja and clay). Red dots represent LOOP sample stations.

A map of the surface geology is shown in Figure 4.3. Glacial tills are dominating the study area. North of the study area there are occurrences of meltwater sands, which are described in boreholes as the "White Sand". This local unit is almost pure quartz sand – presumably not meltwater sand as indicated on the map, but more likely a layer deposited by wind in an ice-free period during the Weichselian; see later description. Postglacial freshwater deposits are found locally in topographic lows in and around the Lillebæk area (Figure 4.3).

The extent of the Late Weichselian Belt Sea advance is visualised on Figure 4.4. The Lillebæk LOOP area is shown with a red circle and is located rather close to the margin of the Belt Sea advance (C).

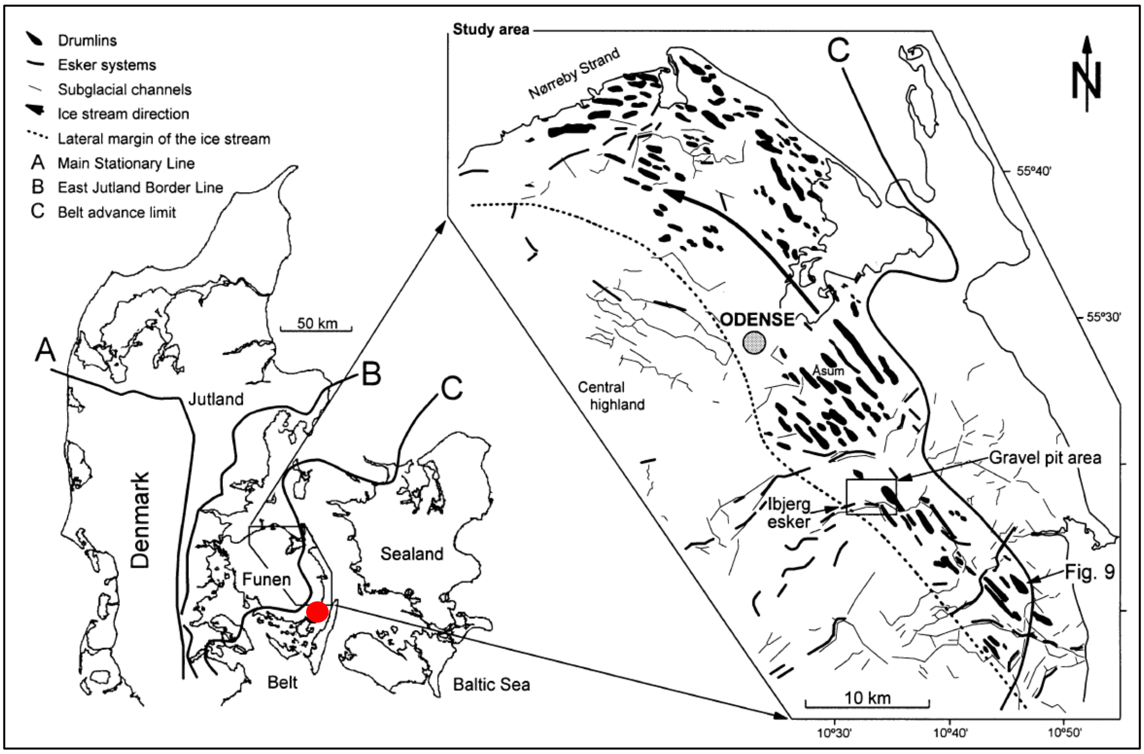


Figure 4.4: Overview of ice advances and ice margins on Funen (Jørgensen and Piotrowski, 2003). Red dot marks location of LOOP 4.

4.2 Geophysical data and boreholes

Four types of geophysical data have been collected in and around the LOOP area (Figure 4.5):

New data collected in MapField:

- tow-TEM data (tTEM; shown as small black dots) (Aarhus University 2020)

Existing data:

- SkyTEM data (airborne Transient Electro Magnetic method) shown as red dots (survey from 2012)
- TEM40 data (ground-based Transient Electro Magnetic soundings) shown as red squares (data from 1999)

- PACES data (Pulled Array Continuous Electrical Sounding) shown as purple lines (data from 1999)

The geological data comprise boreholes from the Jupiter database (black dots).

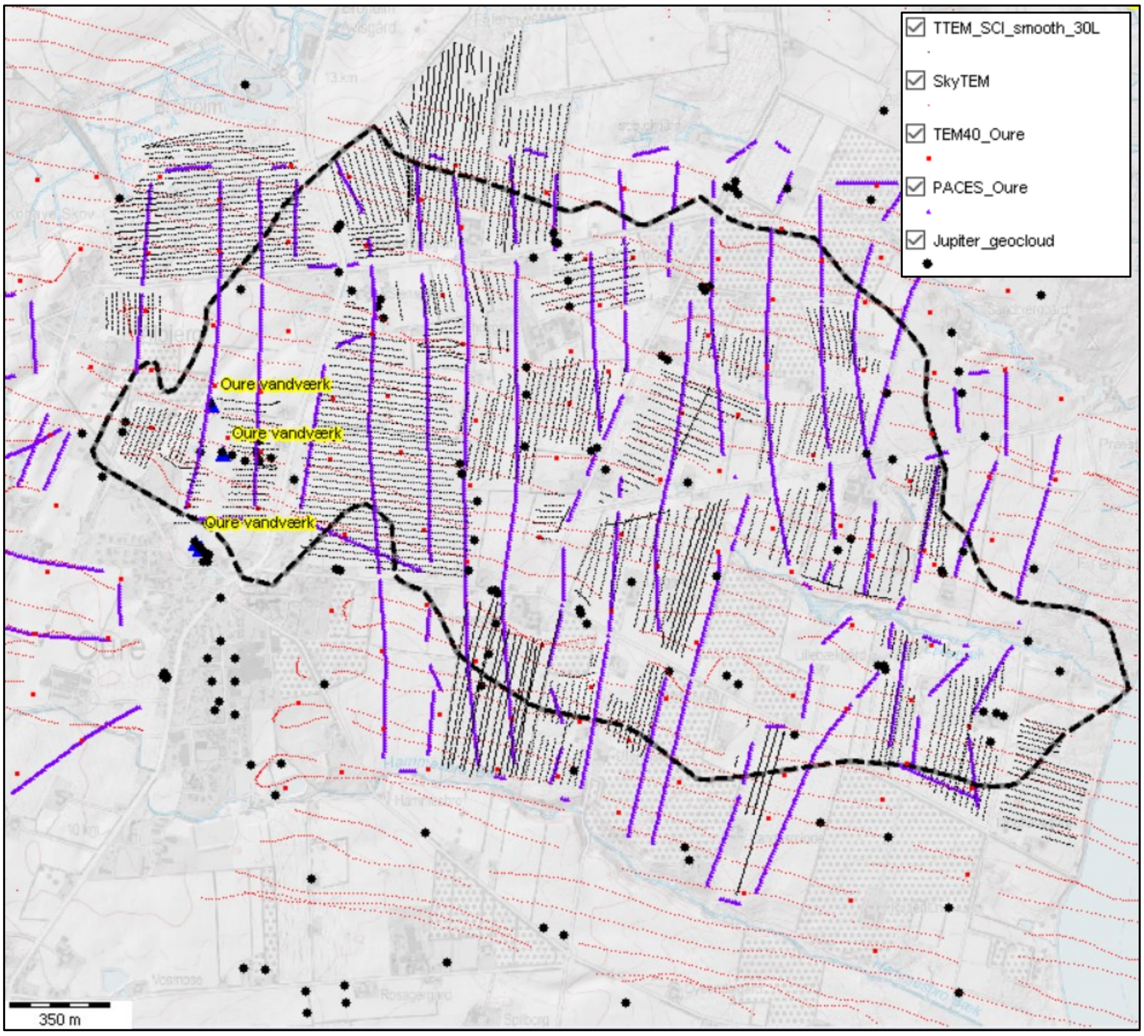


Figure 4.5: Boreholes (Jupiter database) and geophysical datasets (Gerda database) in the area.

As a part of the research project NICA (nitrat.dk) the area has been covered with a SkyTEM survey in 2012. These data provide information additional to the tTEM data which has a patchy coverage in the area. The PACES data has only been partly used in the interpretations.

The boreholes in the LOOP area are mostly shallow and only five of them are deeper than 25 m. Three of these deeper wells are associated with Oure Waterworks located in the western part of the area; see yellow labels on Figure 4.5.

4.3 Stratigraphy

Pre-Quaternary

The island of Funen is located on the NW-SE trending Ringkøbing-Fyn High (red lines on Figure 4.6, left). On this structure, NW-SE and N-S orientated faults have been mapped below Funen (‘Fyn’), see Figure 4.6, left. To the right the top of the pre-Quaternary surface is visualised, showing that the uppermost pre-Quaternary sediment consists of Lower to Upper Paleocene deposits. Figure 4.6

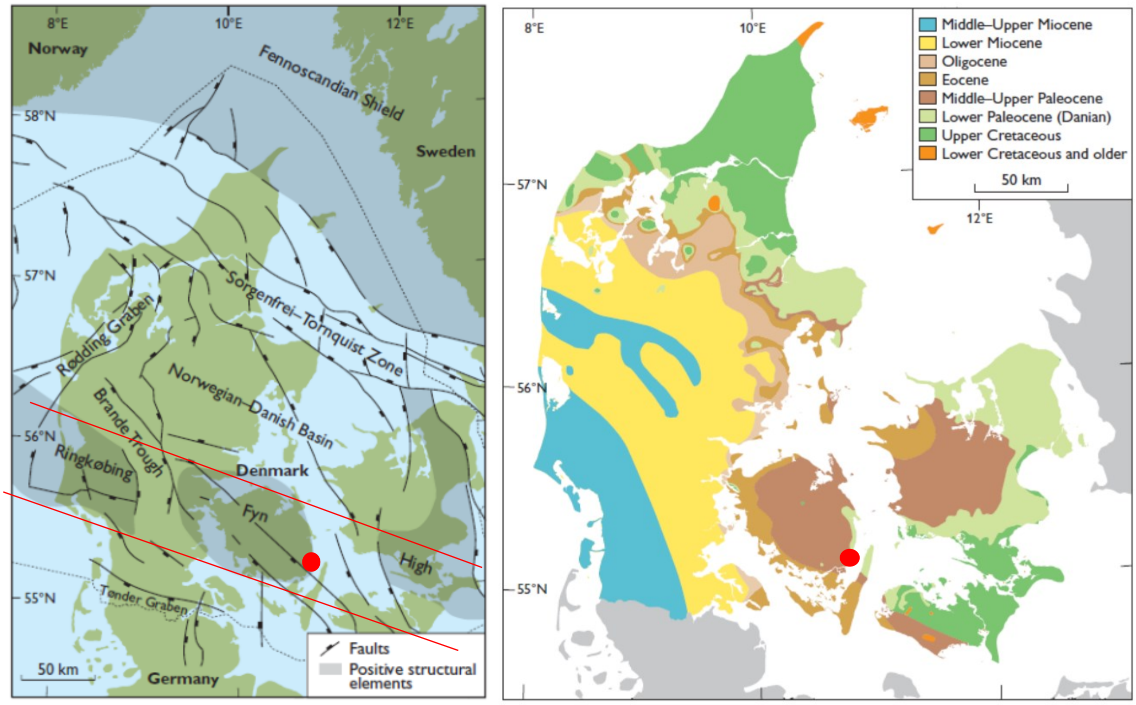


*Figure 4.6: **Left**: Deep-seated tectonic structures – Ringkøbing-Fyn High. **Right**: Pre-Quaternary sediments (both from Rasmussen et al. 2010). The Lillebæk LOOP area is shown with red dot.*

The uppermost pre-Quaternary deposits consist of Paleocene clay of varying thicknesses with Danian limestone and Cretaceous chalk below. The Danian Limestone is up to 50 m thick.

Geological interpretations on the neighbouring island Langeland, 5 km east of the LOOP area, show downfaulting of Limestone blocks with the consequence that Paleogene clays have avoided erosion in a W-E/NW-SE graben structure during the Quaternary glaciations (Andersen et al., 2016); see Figure 4.7. Further to the east, seismic investigations and interpretations offshore in the Great Belt east of Langeland also find a graben structure in the pre-Quaternary succession (Al Hseinat & Hübscher 2017). Some of the faults appear to offset the seafloor pointing to very recent movements along the faults. The LOOP 4 area is situated just west-northwest of the Langeland study site, and therefore it is likely that the graben structure found at Langeland also can be found in the LOOP area.

An interpretation of the geological setting has been made while mapping buried valleys in the area; see Figure 4.8 (Sandersen and Jørgensen, 2016). The interpretation fits well into the geological understanding of the deeper succession described further in the following sections.

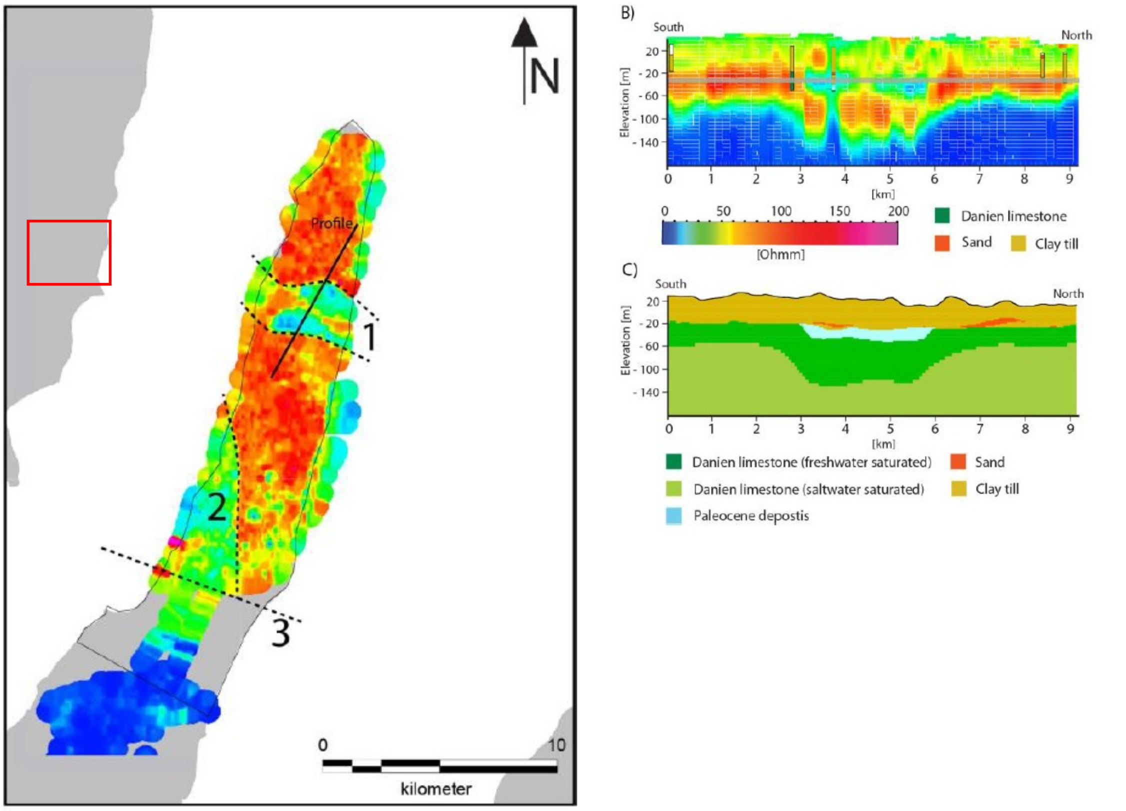


*Figure 4.7: SkyTEM survey at Langeland (from Andersen et al. 2016). **Left**: Resistivity grid at elevation -25 m a.s.l. '1' indicates area of down-faulted limestone and chalk. The LOOP area is marked with a red square 5 km to the west. **Right**: B) SkyTEM resistivity profile and C) Geological interpretation.*

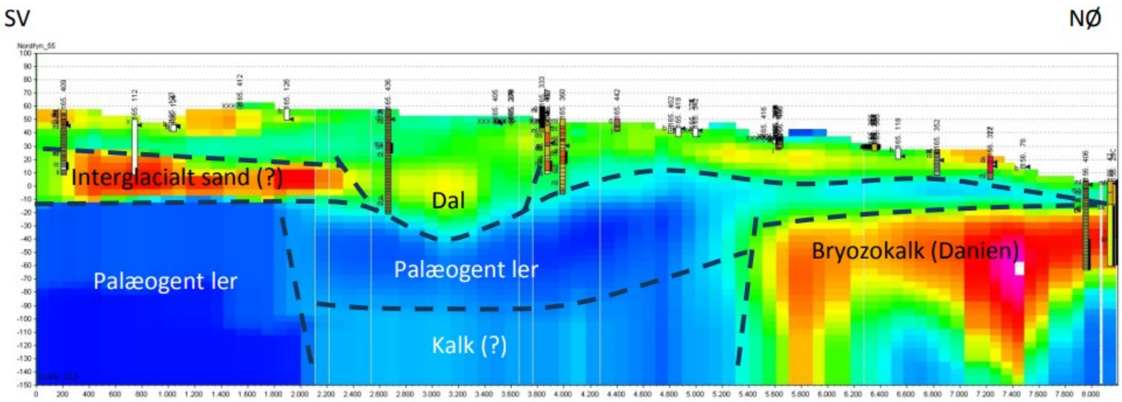


Figure 4.8: Geological interpretation of the buried valley ('dal') ODE11 (from www.buriedvalleys.dk).

Quaternary

The Quaternary succession consists of clayey tills, meltwater sand, meltwater clay, and quartz sand. The Quaternary succession varies in thickness from approx. 15 m and to more than 60 m. Many ice advances have covered the LOOP area resulting in a complex Quaternary stratigraphy (Houmark-Nielsen, 2005). Especially in the higher elevations in the western part of the area, glaciotectonic deformations seem to be widespread.

To the north and the northeast, in- and outside the LOOP area, a more or less continuous sand deposit is identified. The sand deposit is known as the "White Sand" and heavy mineral analyses show that the deposit consists of 96 % quartz grains that are well rounded (Friis &

Larsen, 1975; Larsen, 2002). The sand is interpreted to be wind-deposited during an ice-free period of the Weichselian. The sand is generally calcium free and, in some boreholes, the sand is interpreted as interglacial.

Generally, the area has only a few deep boreholes, but still the lithological information from the boreholes gives a good impression of the sedimentary succession and fits well with the surface geology map (Figure 4.3) (keeping in mind that the sand described as meltwater sand in the surface geology map is believed to be the wind-deposited quartz sand). However, the varying Quaternary sediments at depth makes the interpretation of tTEM resistivities challenging.

4.4 Buried tunnel valleys

Figure 4.9 below, shows buried valleys mapped outside the study area. The buried valleys were formed as tunnel valleys underneath the ice sheets during the Quaternary. As can be seen on the map, one poorly documented valley (ODE11) has been mapped southwest of the LOOP area (Sandersen and Jørgensen, 2016). The infill of the mapped valley system ODE11 is dominated by clayey sediments (clay till and meltwater clay).

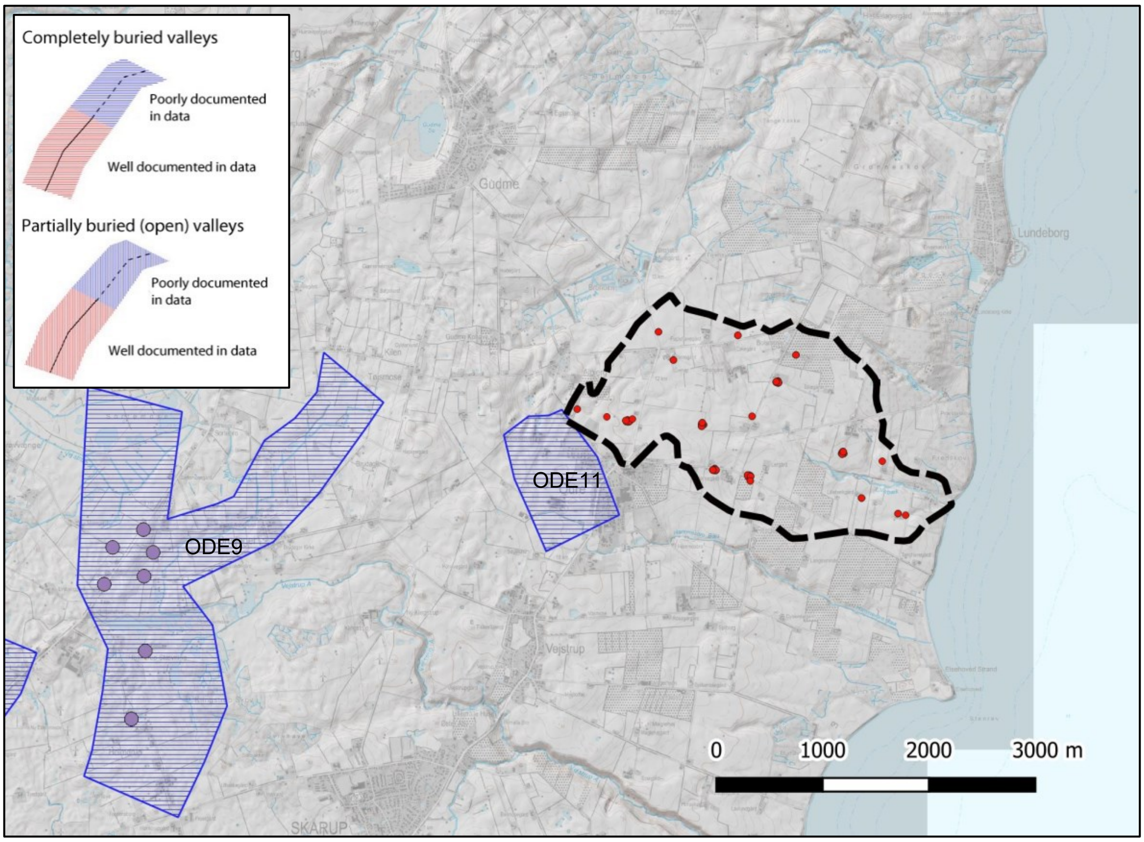


Figure 4.9: Mapped buried valleys close to the study area (shown with black hatched line). Legend for the map is shown above, left (Sandersen & Jørgensen, 2016; www.buried-valleys.dk).

4.5 Geological interpretation of geophysical data

The Lillebæk LOOP area has a full SkyTEM coverage (Figure 4.10) which provides valuable information on the deeper parts of the geology, and adds information of the near-surface sediments where there is no tTEM survey. The tTEM cover is patchy and a combined interpretation with SkyTEM is therefore important. PACES data are also included but are less useful in the interpretation, because the tTEM and SkyTEM data provide a better resolution. Cross-sections through the tTEM, SkyTEM and boreholes are shown on Figure 4.10 and described in the following. SkyTEM data is visualised as single sounding poles on the cross-sections, while the tTEM data are shown as a 3D resistivity grid with a 25 x 25 x 2 m discretization.

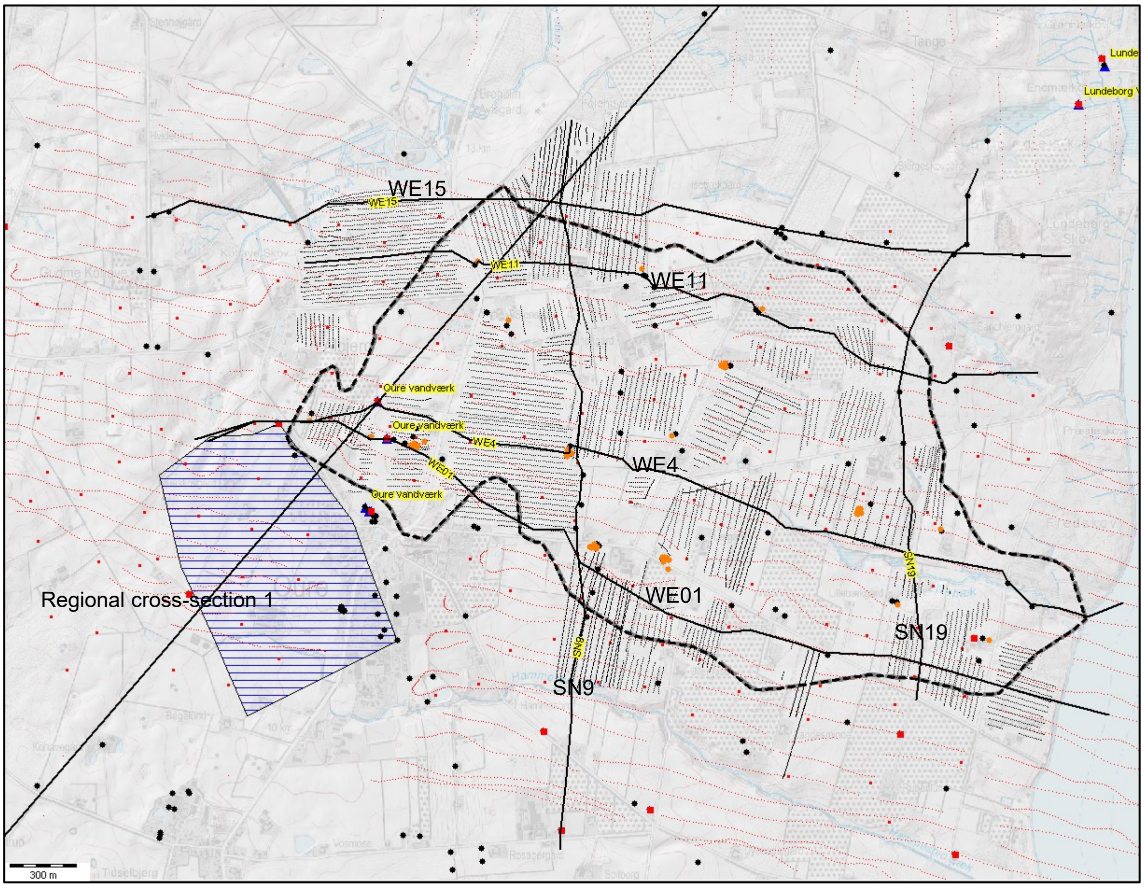


Figure 4.10: Cross-section overview: Black lines, tTEM: black dots, SkyTEM: red dots, MEP: green lines, Boreholes: black dots. LOOP 4 area: black dashed polygon.

In the following, interpretations have been performed on the cross-sections shown in Figure 4.10 and on selected 2D resistivity maps (Figure 4.11).

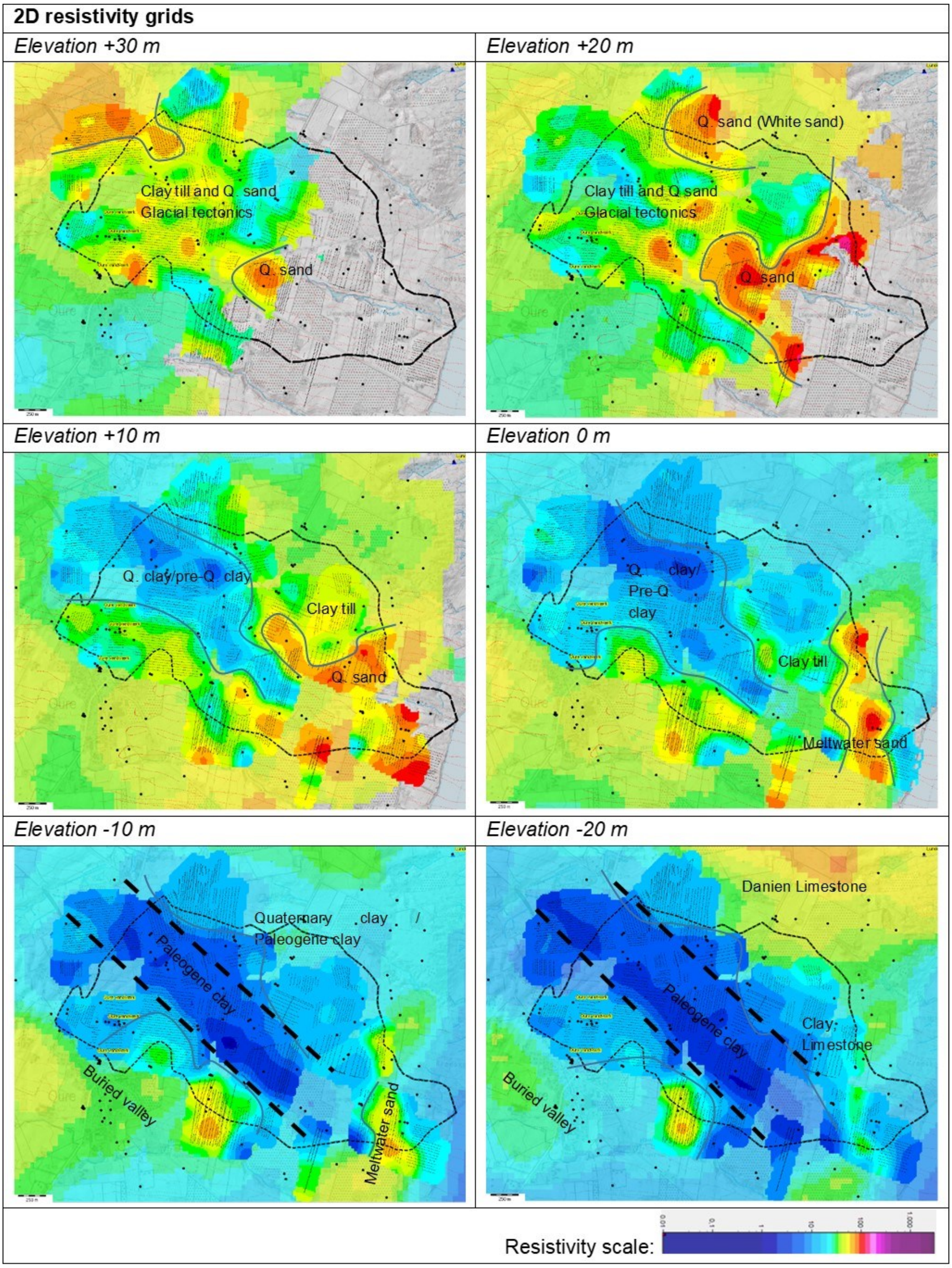


Figure 4.11: 2D resistivity grids of the tTEM dataset (tTEM smooth models, 30 layers, 100 % opacity). Background outside the area mapped with tTEM, are combined 2D resistivity slices for TEM40 and SkyTEM (opacity 60 %). Black dots represent boreholes from the Jupiter database.

Figure 4.11 shows six slices of tTEM 3D resistivity grids with an underlying SkyTEM resistivity grid (partly transparent, opacity 60 %) at the selected elevations. TTEM models are represented by 2 m slices at elevation +30, +20, +10, 0, -10 and -20 m a.s.l., while the SkyTEM data is represented by slices of 5 m at the same elevation. The slices give an overview of the boundaries between mapped near surface Quaternary sand deposits and the predominant clay till cover towards the higher grounds in the west. The sand deposits ('White sand' and meltwater sand) show moderate to high resistivities, whereas the clay till and meltwater clay show low to moderate resistivities (blue-greenish colours). Parts of the upper clay till show low resistivities, which is expected to be due to reworked Paleogene clays in the till.

At the deep levels (approx. 0 m a.s.l. and downwards), very low resistivities are seen in large parts of the area. This is interpreted as a transition from Quaternary deposits to the down-faulted Paleogene clays inside the graben structure. At elevation -20 m a.s.l., especially to the north, higher resistivities represent the boundary to the limestone containing fresh groundwater. To the southwest, a buried valley (ODE11) with clay till infill is represented by moderate resistivities.

Figure 4.12 below is a 10 km long regional profile oriented SW-NE. It crosses the LOOP area from 5500 to 7500 m and gives an overview of the deeper geology. As mentioned in e.g. Sandersen & Jørgensen 2016, it is proposed that fault activity has preserved Paleogene clays up to around elevation 0 m in the LOOP area as indicated on the cross-section. Changes in the resistivity at 6500 m is interpreted to represent a fault zone where the top of the Danian limestone is found at lower elevations (-35 to -25 m a.s.l.) compared to the north-east (-15 m a.s.l.). Paleogene clays are thin or absent northeast of the fault. SkyTEM resistivities indicate saline groundwater in the Danian limestone below -70 to -60 m a.s.l. to the northeast and southwest. Low resistivities in the limestone above this level in the central and southwestern parts of the cross-section point to brackish groundwater. It should be noted that the depth of investigation of the tTEM in the LOOP-area prevents interpretations below the Paleogene clay.

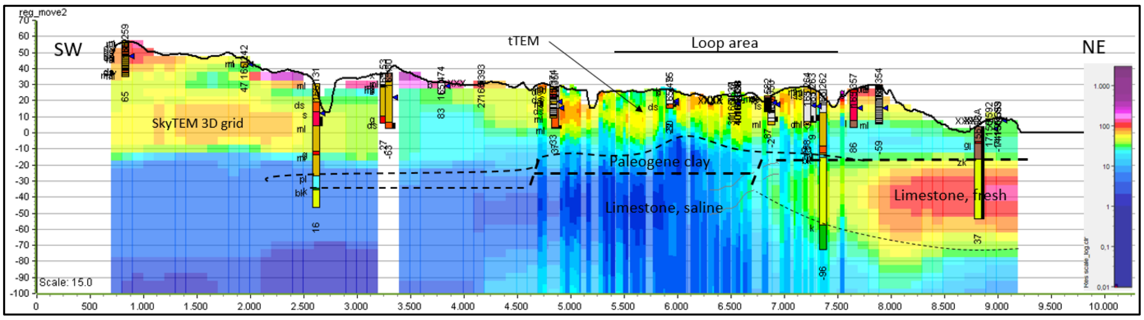


Figure 4.12: Regional cross-section 1, SW-NE. For location, see Figure 4.10. TTEM data are shown as single sounding poles and SkyTEM data are visualized as a 3D resistivity grid.

Cross-section WE01 (Figure 4.13) gives a W-E overview of the southern part the study area, from the high elevations (+50 m a.s.l.) in the west towards the coastline in east. The transition to the Paleogene in the central part stands out quite clearly in the geophysical data - going from high resistivities (interpreted as meltwater sand/White Sand?) to resistivities below 10 Ohmm (blue colours). As sketched in the cross-section, the western part of the Quaternary succession is the most difficult to interpret as it is expected to be disturbed by glacial deformation. Rather thick deposits of older clay till and meltwater clay is expected on top of the Paleogene in the western part, whereas the Quaternary succession is expected to be thin (< 15 m) to the east.

A 10-20 meter thick sand layer from 2200-3600 m is interpreted by use of both borehole data and TEM data. It reaches the terrain surface and is generally described as meltwater sand and not the ‘White Sand’ as samples from boreholes show a content of calcium. The quartz sand/White sand is normally free of calcium and is described in the northern part of the LOOP area. Generally, an upper glacial till presumably deposited during the latest ice advance (Belt Sea advance), is found throughout most of the LOOP area. The clay till shows quite low resistivities probably due to Paleogene clay that has been incorporated in the clay till. At 3600-4000 m on the cross-section WE01, high resistivities indicate a buried valley with an N-S trending orientation apparently parallel with the coastline.

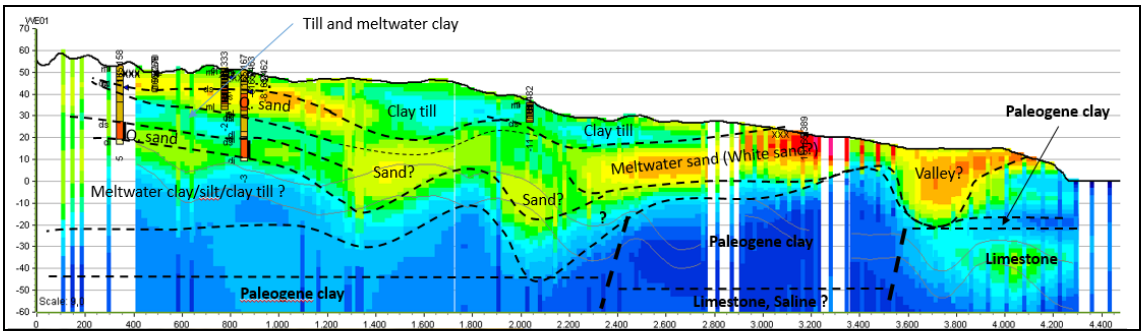


Figure 4.13: Cross-section WE01, W-E. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid. SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section in Figure 4.14 (WE4) crosses the LOOP area from west to east, see location on Figure 4.10. The cross-section shows the same picture as WE01: a) a glacially deformed Quaternary sequence above +30 m a.s.l.; b) a sand deposit (meltwater sand/White Sand) in the central part with an upper till cover that is almost non-existing towards the east; c) a block of Paleogene clay west of a suggested fault line (at 3000 m) and d) a possible valley with sand infill in the eastern part of the LOOP area close to the coastline.

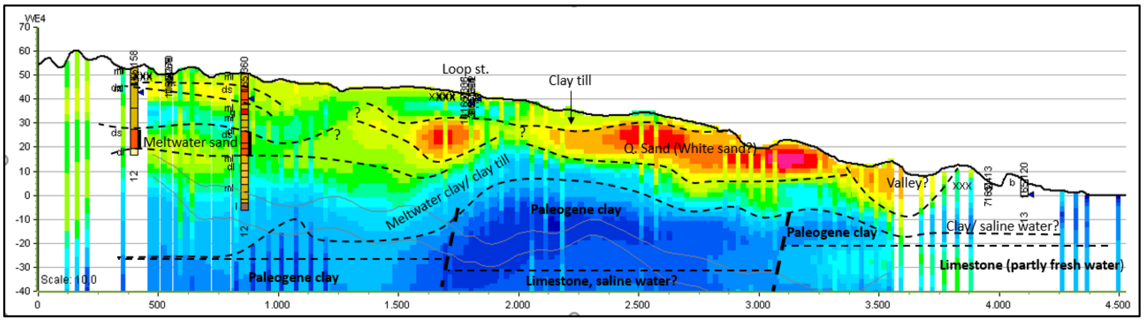


Figure 4.14: Cross-section WE4, W-E. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid. SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section WE11 in Figure 4.15 illustrates somewhat the same as the prior cross-section, but it crosses the northern part of the LOOP area. In this section, the data indicate a less deformed sequence. The moderate to high resistivities shows a more consistent sand layer that can be followed throughout the area with an estimated thickness varying between 10-20 m. At 3200 m (East), borehole DGU no. 165.263 describes quartz-rich sand with no calcium content, here interpreted as the “White Sand”, but specified as interglacial sand in the geological description in the Jupiter database. It is likely that this is the same sand unit that can be followed inland to the west. The clayey till cover above the sand deposits varies from less than 5 m to more than 15 m. The till cover is thinnest to the west (0-400 m at the cross-section) and east (2800 m – 3400 m). Below the resistive sand layer, the resistivities are moderate to low, which combined with borehole information is interpreted as clay till and meltwater clay. The pre-Quaternary in the west is again expected to be Paleogene clays of significant thickness while the higher resistivities in the eastern part of the cross-section represent limestone with fresh water.

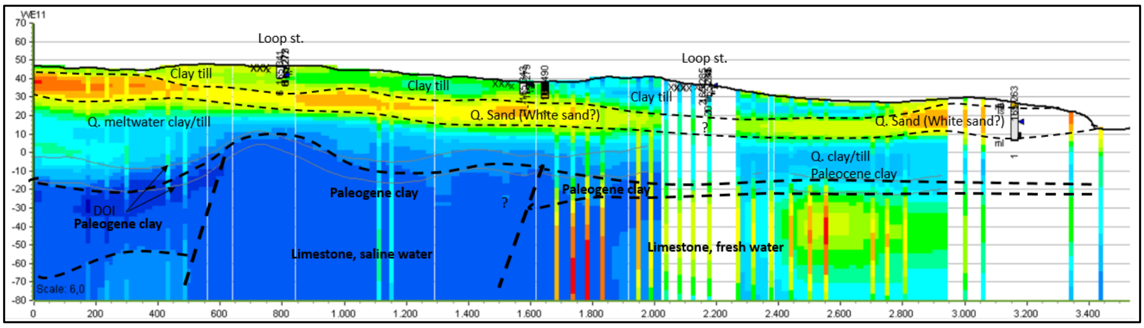


Figure 4.15: Cross-section WE11, W-E. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section WE15 in Figure 4.16) crosses like WE11 the study area in the northern part of the LOOP area. The possible wind deposited "White sand" is described in two boreholes (DGU no. 165.352 and 165.354) at 3500 m and 4100 m and is also known from an old sand pit just north of the LOOP area. It is therefore very likely that this sand layer can be followed towards west as interpreted on the cross-section. In the eastern part, the sand aquifer is overlying older clayey tills represented by moderate-low to low resistivities indicating influence from the Paleogene deposits.

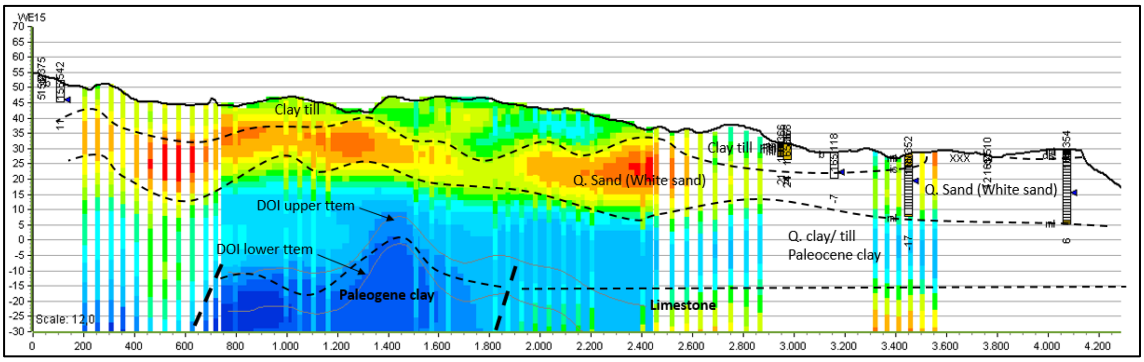


Figure 4.16: Cross-section WE15, W-E. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section SN9 (Figure 4.17) is oriented South-North crossing the LOOP area from 1000 m to 3000 m. The Paleogene clay stands out in the TEM data. South of the Paleogene clays at 800 m to 1400 m it is likely that another fault line is present. The geophysical data show moderate resistivities down to -30 to -35 m a.s.l., which could indicate a buried valley (maybe connected to the same system as the buried valley ODE11). The Quaternary seems to be glacially deformed from 600-1700 m and it is difficult to resolve any deeper sand units below elevation 0 m a.s.l. in this section. The shallow boreholes at 1400 m to 1800 m describe mostly clay till, but also meltwater clays and meltwater sand indicating that the upper part in this area is complex and most likely glacially deformed.

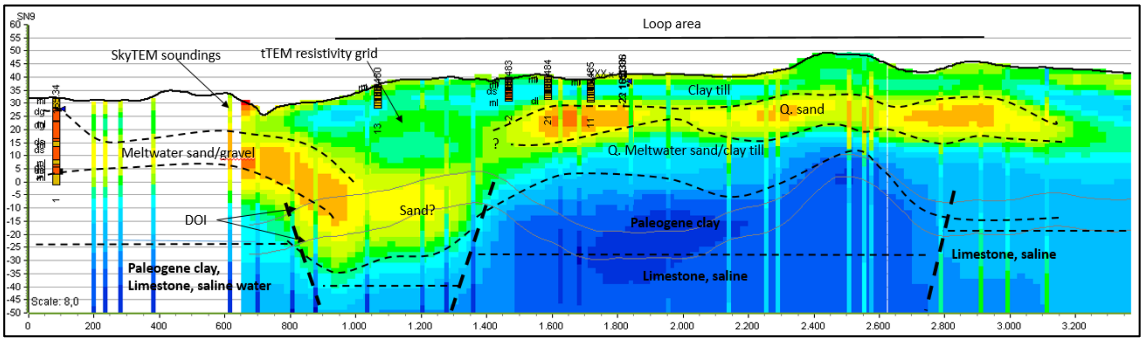


Figure 4.17: Cross-section SN9, S-N. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

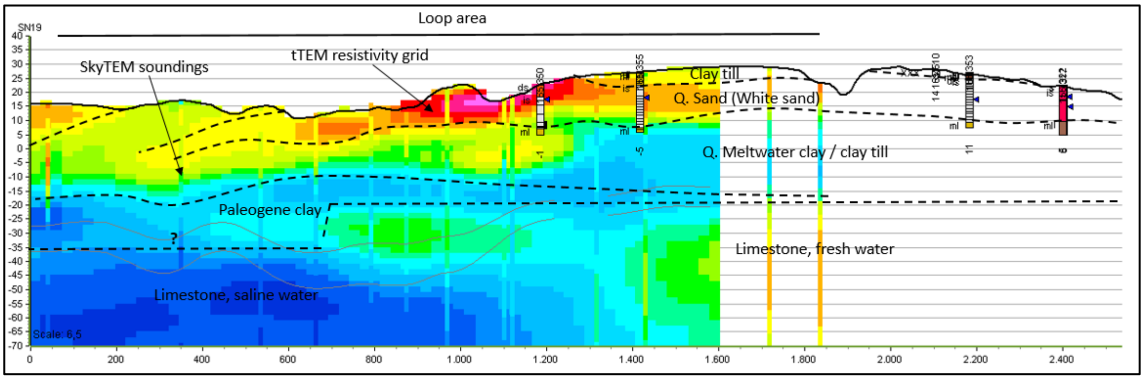


Figure 4.18: Cross-section SN19, S-N. For location, see Figure 4.10. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section SN19 (Figure 4.18) strikes S-N through the eastern part of the study area and illustrates the change in geology going from the lower parts in south with moderate resistivities, crossing Lillebæk at 650 m, to the area with sand described as interglacial sand (White Sand) close to the surface. Beneath the sand deposits, all boreholes describe clay till.

To summarize, the following geological characteristics can be pointed out in the geological interpretation:

a) An upper Late Weichselian clay till unit covering most of the area with thicknesses of less than 3 m to more than 15 m. In some parts the resistivity of the till is quite low indicating mixing with Paleogene clay.
b) In the northern and eastern part of the area, a rather continuous sand layer could be interpreted as the Weichselian ‘White Sand’. The local quartz sand unit is possibly deposited by wind, but is described as “normal” meltwater sand in terms of colour in the Jupiter database, it is calcium free, and the grains are well rounded. To the south and southwest, it becomes more difficult to follow this sand unit. The unit reaches the terrain level in some areas.
c) In the southwestern part of the LOOP area at elevations above 30 m a.s.l. and towards the town of Oure, TEM data and boreholes indicate an area of large geological heterogeneity due to glacial deformation.

d) In the eastern part, a possible S-N trending buried valley with infill of mostly meltwater sand has been identified.
e) The pre-Quaternary succession is characterized by the presence of Paleogene clays due to downfaulting of the limestone/chalk deposits. To the north, the top of the limestone is found at -15 m a.s.l. and characterized by moderate to high resistivities in TEM indicating fresh porewater. The outline of the pre-Quaternary surface is mainly interpreted using TEM because of lack of deeper boreholes.

4.6 Characterizing geological elements

Based on the interpretations, three geological elements representing the LOOP 4 area have been outlined. The delineated elements are sketched in Figure 4.19 and comprise the following:

- **GE1:** The pre-Quaternary clays and limestone (containing fresh and saline groundwater). The deposits have been displaced by tectonics.
- **GE2:** A deeper Quaternary sequence expected to be dominated by clay till and meltwater clays, but also containing buried valley sediments in the eastern part.
- **GE3:** An upper Quaternary sequence characterized by interglacial sand deposits ("White sand"), meltwater sand and an upper clay till.

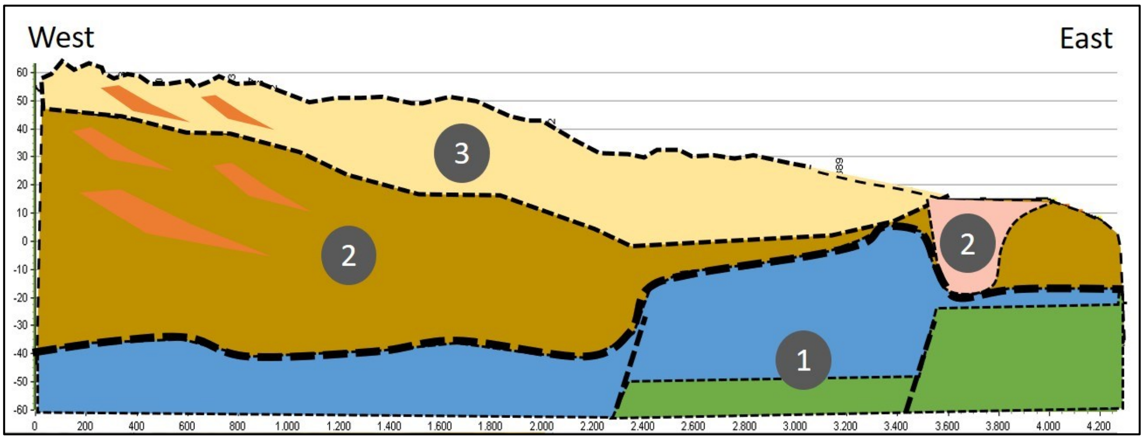


Figure 4.19: Sketch visualizing the delineated geological elements within LOOP 4.

4.7 Summary and conclusions

- **Geophysical mapping:** The area has a good coverage with geophysical data (tTEM and SkyTEM data). The data in combination has greatly improved the understanding of the geological setting. The tTEM provides a better resolution compared to the existing SkyTEM soundings, but the full SkyTEM coverage in the area has been useful in the interpretation because the data adds information below the tTEM DOI.

- **Borehole information:** The information from boreholes is sparse as many of the boreholes are shallow, but the general perception of the upper succession is fairly good. The top of the pre-Quaternary sequence is only penetrated by a few boreholes and therefore the interpretations of the surface of the Paleogene and the limestone is highly dependent on TEM data and boreholes outside the LOOP area.

- **Geological interpretation and correlation:** The study area is predominantly defined as a glacial landscape of Late Weichselian age with occurrences of postglacial deposits in low-lying areas. Sediments are clay tills, meltwater clays, meltwater sands and the local occurrence of quartz sand ('White Sand') described in a sand pit and boreholes in the northern part of the area. The TEM data gives good information of where these sand layers are present in the LOOP area. The glacial landscape in the south-western part appears to be glacially deformed, whereas the eastern parts of the Quaternary sequence appears to be more simple. The deeper and older part of the Quaternary succession and the boundary to the Paleogene is difficult to distinguish precisely due to weak resistivity contrasts. Faults in the deeper parts are believed to have caused downfaulting of limestone/chalk blocks and thereby preserved Paleogene clays from erosion. Data indicates a "block" of Paleogene sediments (up to elevations around 0 m a.s.l.). The Paleogene clays has likely been subject to repeated glacial erosion and deformation throughout the Quaternary.

5. LOOP 6 Bolbro

5.1 Geomorphology and surface geology

The Bolbro study area (Figure 1.1) is located on the Late Weichselian Tinglev outwash plain in the southern part of Jutland (Figure 5.1), but small parts of the study area are located on glacial landscape remnants of pre-Weichselian age - called “hill islands”. The Tinglev outwash plain is dominated by meltwater sand. The outwash plain surface has a gentle slope from east to west (see Figure 5.2).

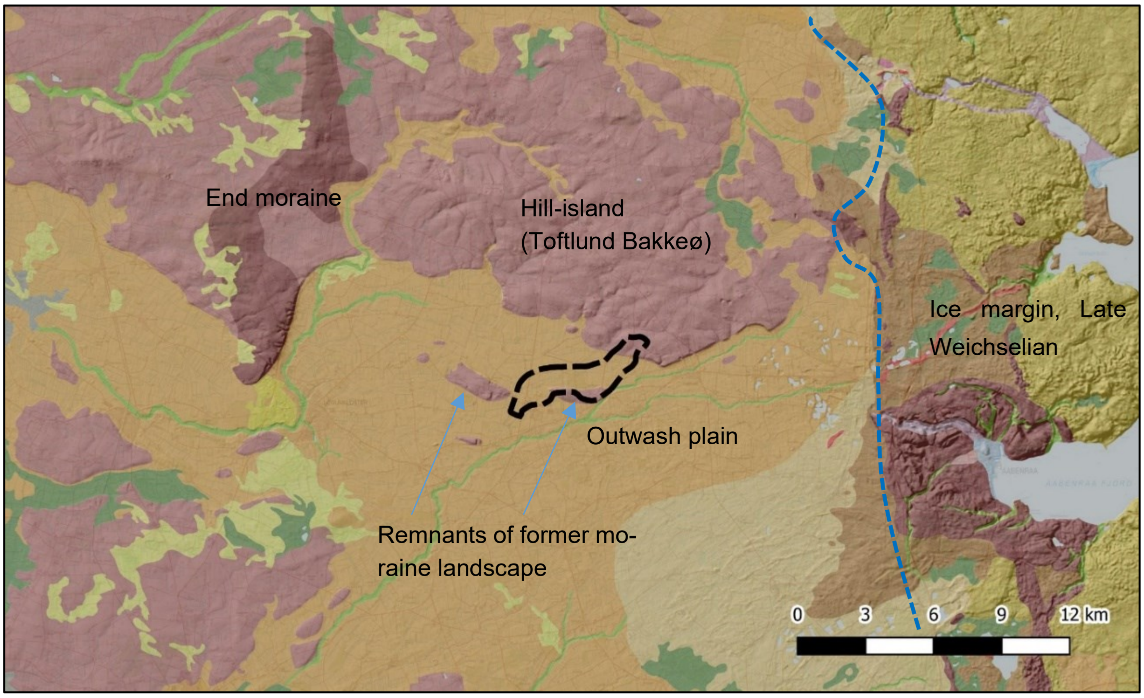


Figure 5.1: Morphological map. Study area marked with dashed black polygon and is primarily located on an outwash plain from the last glaciation (Weichselian) with the ice margin (Main Stationary Line; blue hatched line) approx. 10 km to the east (GEUS, 2018).

The main stationary line of the Late Weichselian ice sheet is located around 10 km east of the study area, representing the ‘Main ice advance’ from northeast (21 kyr BP). The younger ‘East Jutland advance’ and ‘Belt-sea advance’ from southeast (18-17 kyr BP) also drained meltwater through the study area but did not reach as far west (Houmark-Nielsen, 2007).

In the northern part, on the hill island, the elevation reaches 50 m a.s.l., and from the rim of the hill island towards the outwash plain there is a relatively steep drop of 5-10 m. Elevations of the hills island indicate two plateaus – an upper plateau with elevations around 50 m a.s.l., and a middle plateau close to elevation 40 m a.s.l. before the transition to the outwash plain. The general east-west slope on the outwash plain in the study area is around 10 m - from elevation 35 m a.s.l. in east to elevation 25 m a.s.l. in west, see Figure 5.2. The small streams in the area are also shown on Figure 5.2. Most of the streams follow the terrain slope towards west-southwest. The hill island remnants at the southern boundary of the area show elevations up to approx. 40 m.

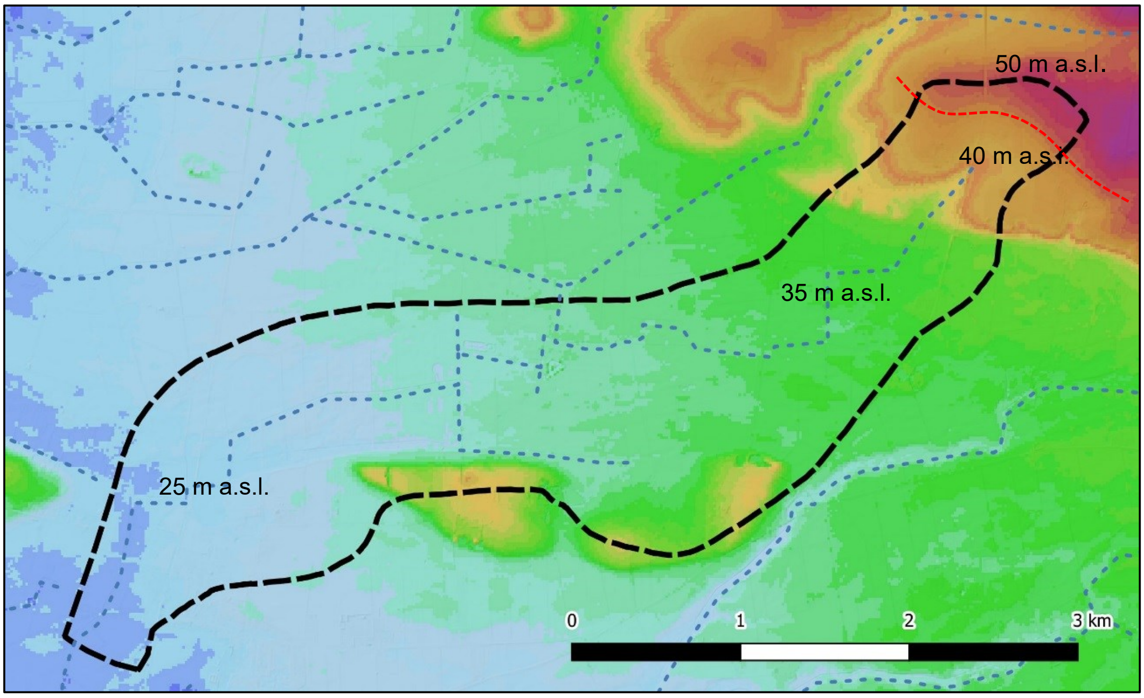


Figure 5.2: Digital elevation model (highest elevations: brown-red, lowest: blue). Blue dashed lines represent the small streams and channels in the area. The red line indicates two plateaus on the hill island.

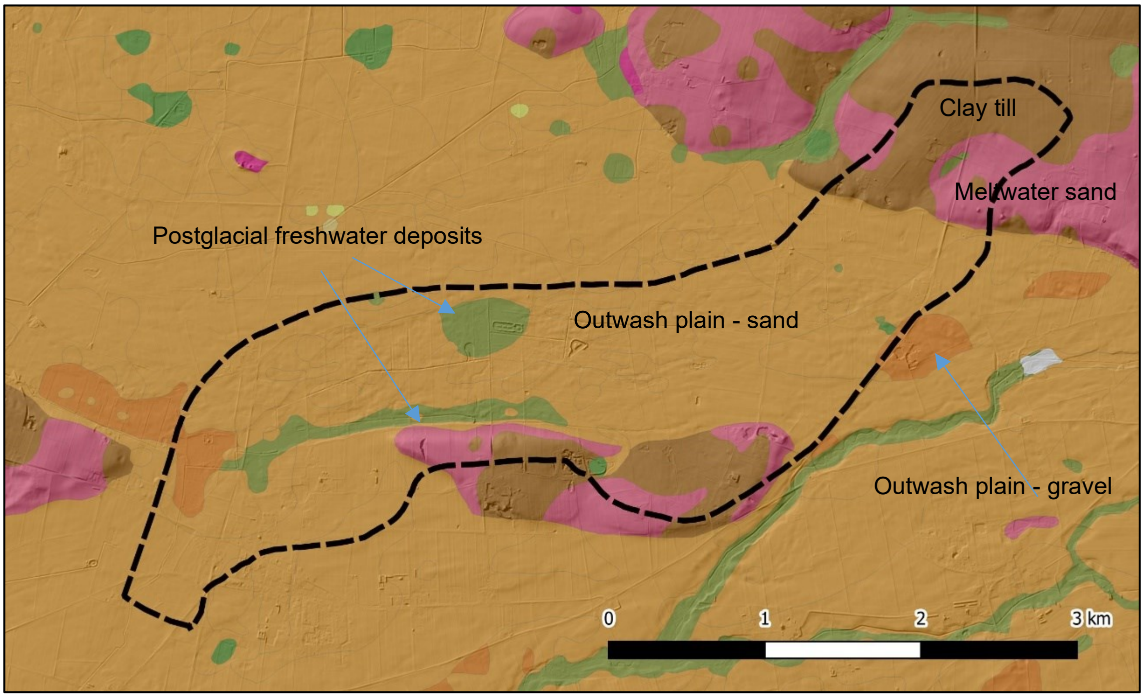


Figure 5.3: Surface geology (the uppermost meter; Jakobsen & Tougaard, 2020). Brown colours: Tills; Red: Meltwater sand; Orange: Outwash sands/gravel; Green: Postglacial freshwater deposits.

A map of the surface geology is shown in Figure 5.3. Outwash deposits (primarily sand) are the dominant sediment type in the study area, but to the north, in the highest parts of the terrain, occurrences of clay till and older meltwater sand deposits are found. Meltwater sand are also found at the lower hill island plateau. Occurrences of postglacial freshwater deposits can be found locally in topographic lows.

5.2 Geophysical data and boreholes

Three types of geophysical data have been collected in and around the study area (Figure 5.4):

New data collected in MapField:

- tow-TEM data, 304 line km with line spacing of 25 m (tTEM; red dots) (Aarhus University 2019c); see also Sandersen et al. 2021.

Existing data:

- SkyTEM data (airborne Transient Electro Magnetic method) shown as purple dots
- MEP data (Multi Electrode Profiling) shown as green lines

The geological data comprise boreholes from the Jupiter database (black dots). Only approx. 15 boreholes are drilled deeper than 25 meters.

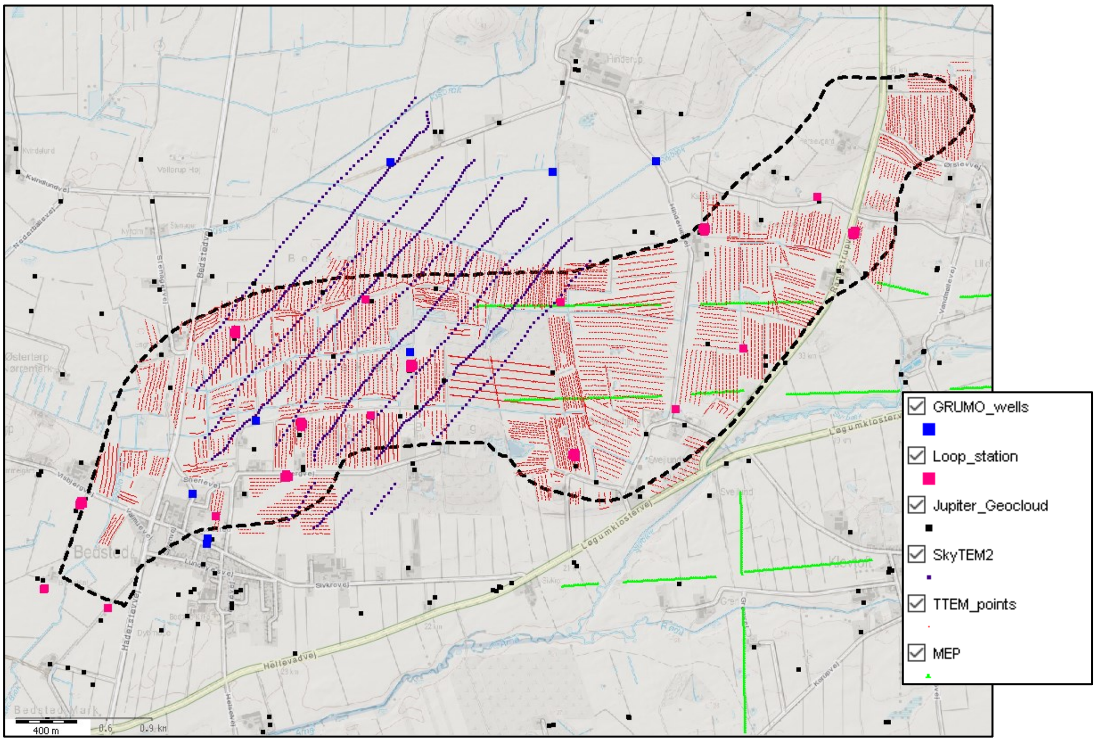


Figure 5.4: Boreholes (Jupiter database; groundwater monitoring, GRUMO and land surveillance, LOOP) and geophysical datasets (Gerda database) in the area. Legend is shown to the right.

5.3 Stratigraphy from boreholes

The oldest parts of the subsurface found in boreholes comprise Miocene sequences of marine clay and sand. Information from important stratigraphic boreholes at Løgumkloster (west), Hellevad and Rødekro (east) and Tinglev (south) have been used to get a stratigraphic overview inside and outside of the LOOP area.

Deep faults have had structural impact on the Miocene deposits in the region, e.g. in the Tønder Graben towards the south (Rasmussen, 2010). The nearest deep stratigraphic boreholes and mapped fault lines are shown on Figure 5.5.

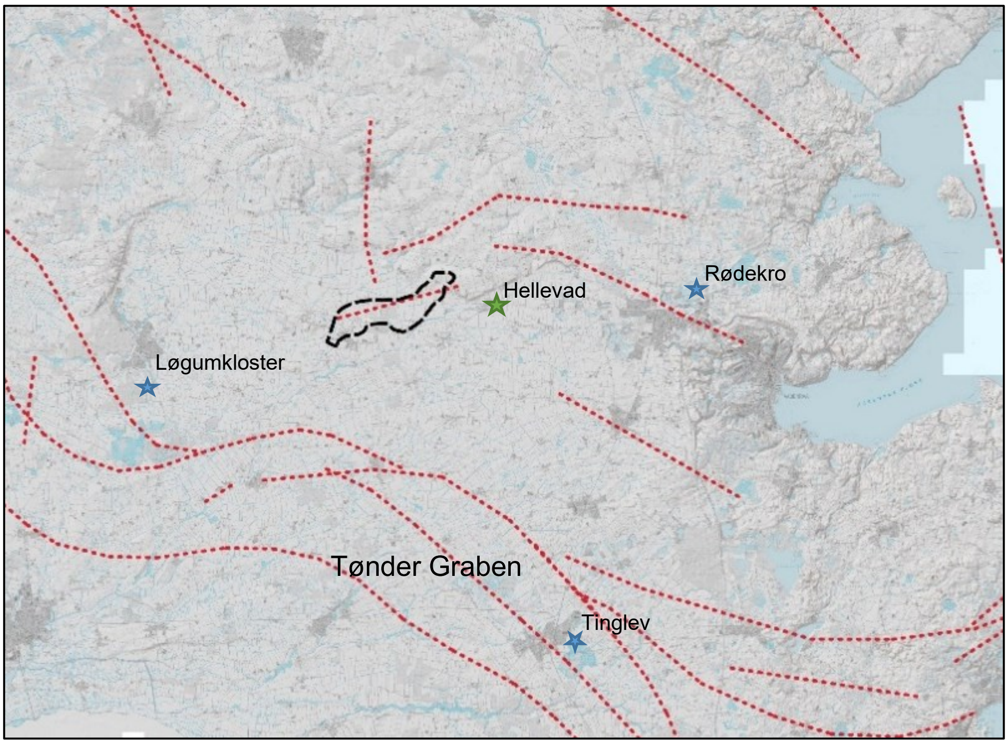


Figure 5.5: Stratigraphic boreholes Hellevad, Rødekro and Tinglev (from Rasmussen, 2010), and mapped deep fault lines in the region and the Tønder Graben (from Sandersen and Jørgensen, 2016).

The Hellevad Borehole (DGU nr. 160.1512) is located 4 km east of the study area and describes a Miocene sequence of sand and clay formations. The Miocene marine clays typically have a high content of organic matter. The upper pre-Quaternary part of the deposits in the study area are thus expected to be represented by Miocene (mica-) sands and mica clays. The boundary between the Quaternary and pre-Quaternary sediments is not straightforward to map from the geophysical data due to lack of resistivity contrasts and significant geological heterogeneity.

The Quaternary succession above consists of meltwater sand, meltwater gravel, clayey tills, and occurrences of meltwater clay. The thickness of the Quaternary succession is interpreted to be more than approx. 40 m. Generally, the area has only a few deep boreholes, but still the lithological information from the boreholes gives a good impression of the sedimentary succession and fits well with the surface geology map (Figure 5.3). However, the varying Quaternary sediments at depth makes the geological interpretation of tTEM resistivities challenging.

5.4 Buried tunnel valleys

Figure 5.6 shows the buried valleys mapped outside the study area. The buried valleys were formed as tunnel valleys underneath the Pleistocene ice sheets, and they are generally between 1 and 2 km wide and some of them have depths of more than 100 m. As can be seen on the map, the valleys mostly have two preferred orientations, one around E-W/ENE-WSW and the other around NNW-SSE/N-S (Sandersen and Jørgensen, 2016).

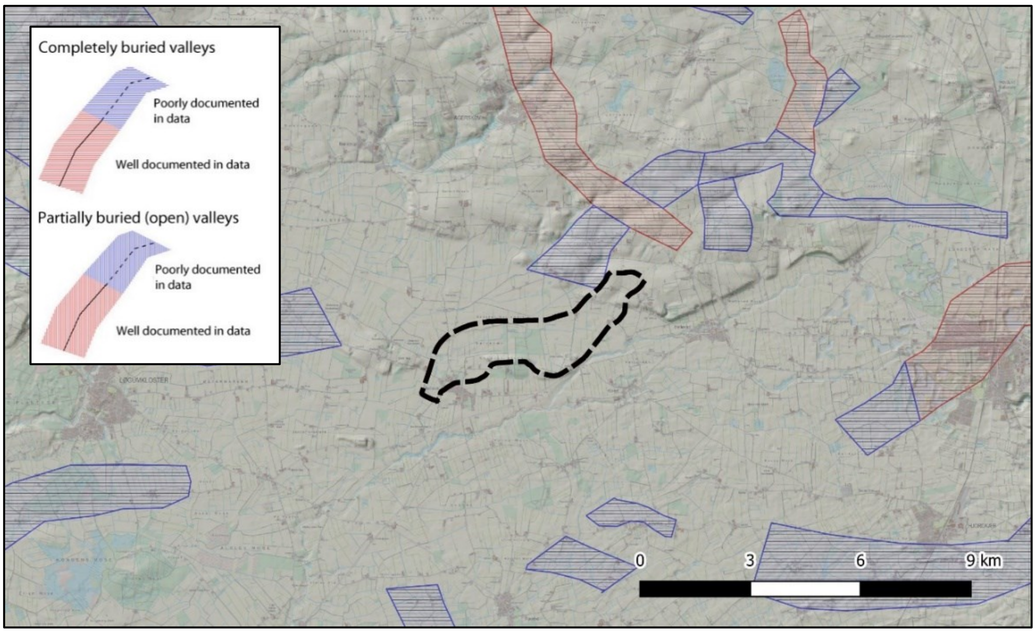


Figure 5.6: Mapped buried valleys close to the LOOP area (shown with black hatched line). Legend for the map is shown above (Sandersen & Jørgensen, 2016) and on www.buriedvalleys.dk).

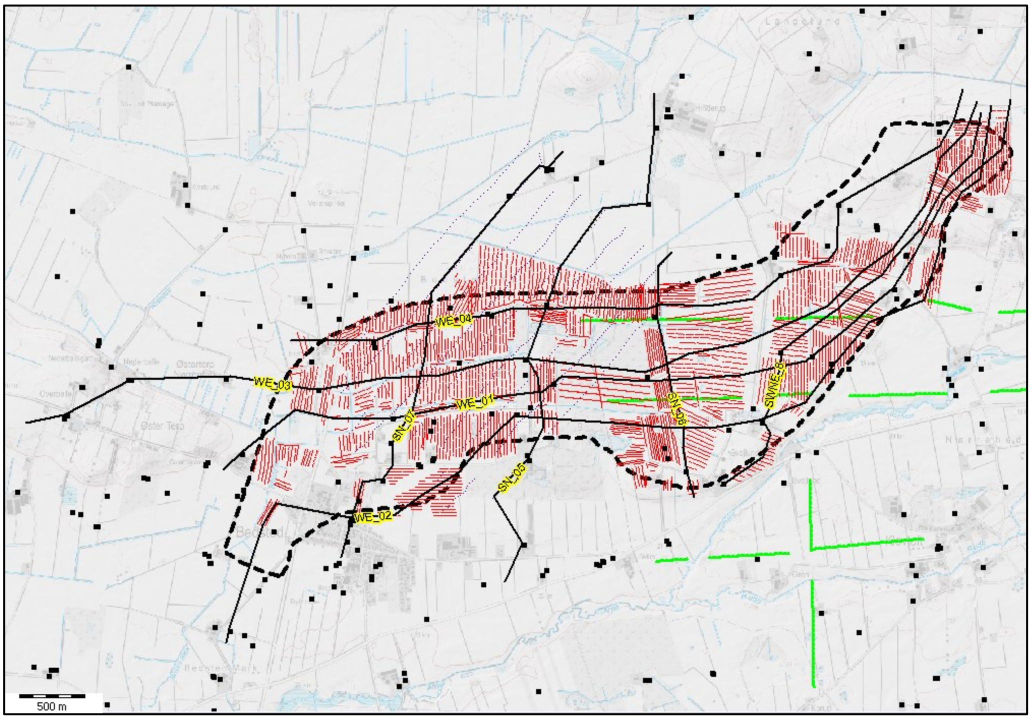


Figure 5.7: Cross-section overview: Profiles: Black lines, tTEM: Red dots, SkyTEM: Small purple dots, MEP: Green lines, Boreholes: Black dots.

The infill of the mapped valley system to the north (RIB39) is dominated by clayey sediments (clay till and meltwater clay). A continuation of this buried valley to the south has not been mapped (Sandersen and Jørgensen, 2016).

5.5 Geological interpretation of geophysical data

The tTEM cover is patchy and although the geology is very varied, the data gives valuable information of the geological setting. The SkyTEM-data is located in the central part north of Bedsted (Figure 5.4) and also provide valuable information. The overlap makes a comparison of the two methods possible. MEP data are also included but are less useful in the interpretation, because the tTEM provides a better resolution. Cross-sections through the tTEM data and boreholes are shown on Figure 5.7, and a number of these profiles are shown in the following. SkyTEM data and MEP-profiles are included on selected profiles.

In the following, preliminary interpretations have been done on the representative cross-sections shown in Figure 5.7 and on selected 2D resistivity maps (Figure 5.8).

Six slices of tTEM 3D resistivity grids are shown in Figure 5.8. The figure shows 1 m slices through elevations -10, 0, +5, +10, +15 and +20 m a.s.l. The slices give an overview of the boundaries between the “hill-island” (glacial) and the sandy outwash plain elements. The “hill-island” geology shows a layer of low to moderate resistivities (blue-green colours) which extends beneath the outwash plain.

Cross-section WE_01 (Figure 5.9), gives an overview of the study area from the west (outwash plain) to the northeast (hill island). Shown on the profile is a 3D resistivity grid of the tTEM dataset and overlapping SkyTEM soundings as single resistivity poles. The bottom of the outwash plain stands out quite clear in the geophysical data - going from high resistivities (red colours) representing sand to moderate resistivities (green colours) representing clay till and meltwater clay. The clay has a very irregular and wavy appearance along the profile and appears to have been glaciotectonically deformed (see also Sandersen et al. 2021). As sketched at e.g. 5000 m on the cross-section, the pre-Weichselian surface is expected to have been exposed to erosion and/or glacial deformation. The present “hill-island” landscape is seen from 6000 m and further to the east. This part of the hill island is dominated by meltwater sand close to terrain. The left side of the profile shows two boreholes (DGU no. 159.308 and DGU no. 159.982) that very well illustrate the varying Quaternary geology found beneath the outwash plain.

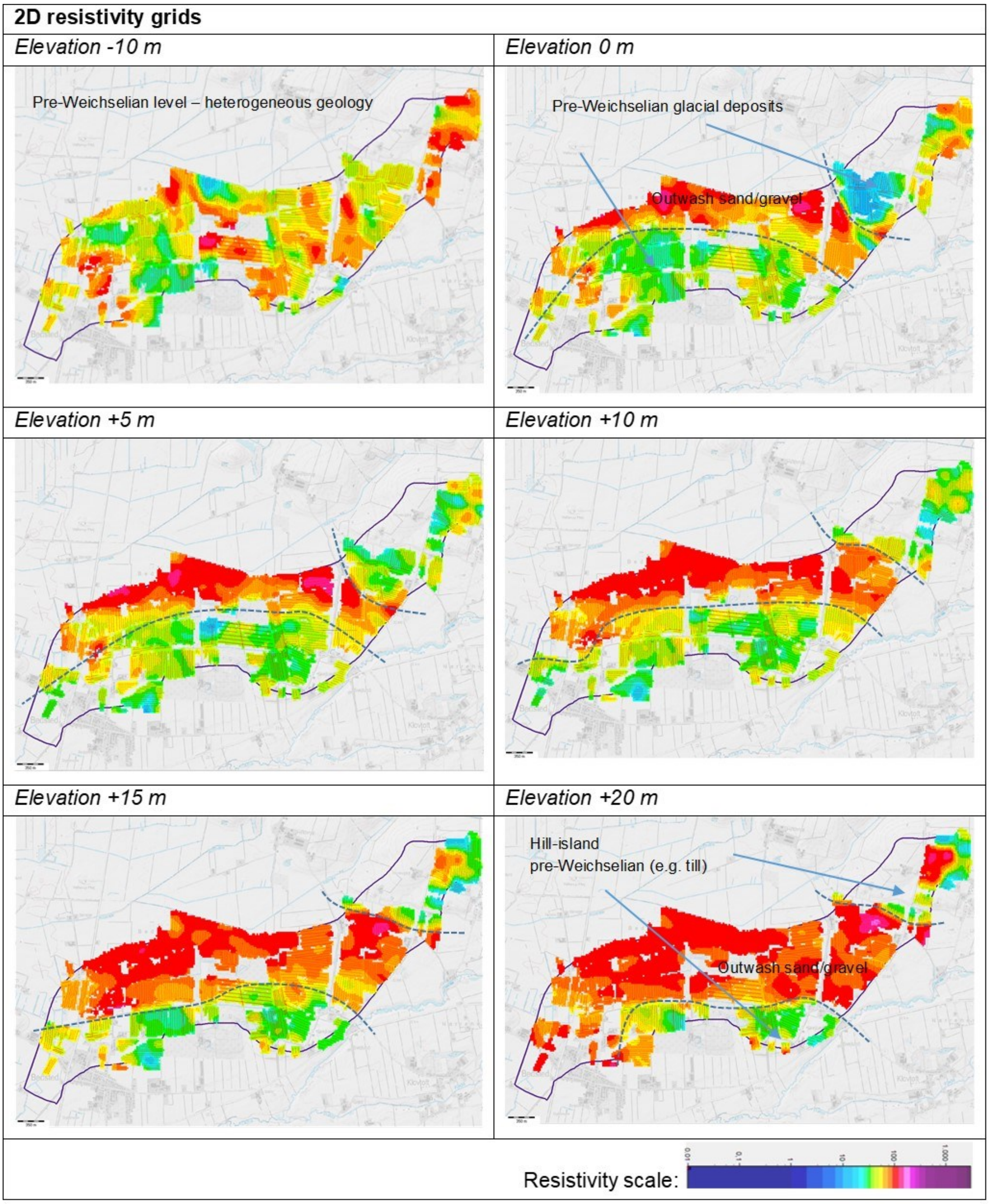


Figure 5.8: 2D resistivity grids of the tTEM dataset (tTEM smooth models, 30 layers).

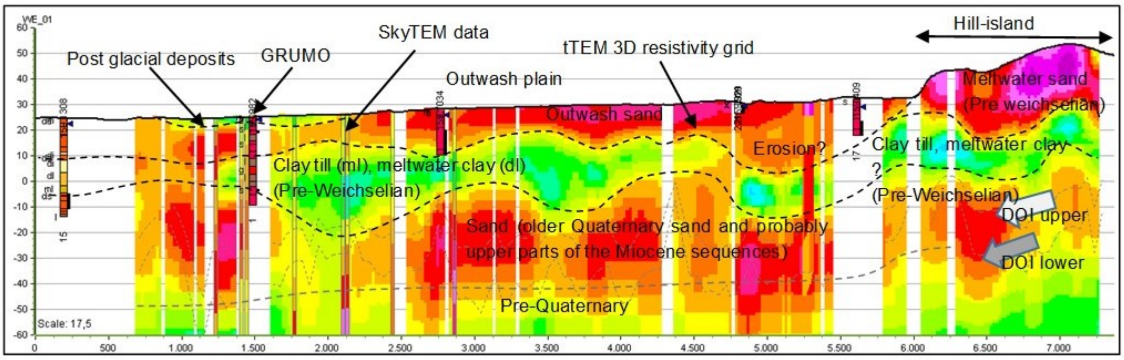


Figure 5.9: Cross-section WE_01, W-ENE. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

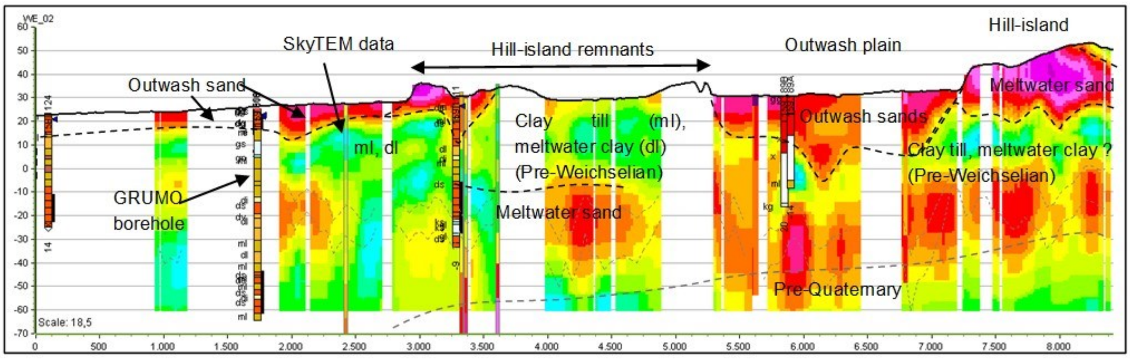


Figure 5.10: Cross-section WE_02, W-ENE. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

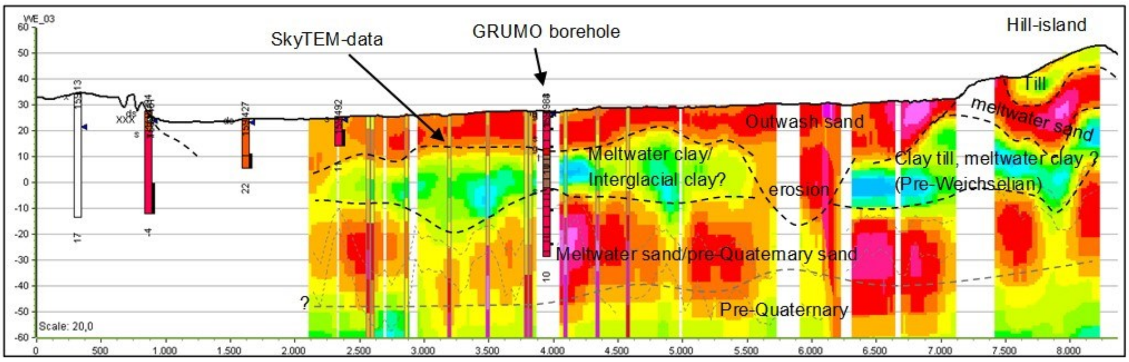


Figure 5.11: Cross-section WE_03, W-ENE. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

The cross-section in Figure 5.10 (WE_02) crosses both areas with hill-islands in the study area. The remnants of hill-islands in the terrain reveal areas with low resistivities reaching the surface. These deposits are described as clay tills in boreholes. The presence of outwash plain sands between the hill-islands (between 5200 and 7200 m) indicate erosion into the deeper, fine-grained deposits. Borehole DGU no. 159.111, at 3300 m, describes meltwater clay and clay till from elevation +10 to -10 m, which correlates well with the low to moderate resistivities in tTEM. Beneath these sediments, a thick layer of meltwater sand is partly resolved in data by higher resistivities and with validation in boreholes.

The cross-section WE_03 in Figure 5.11 illustrates more or less the same as the cross-section WE_02. In addition, the data coverage gives a good understanding of the outwash plain and the upper parts of the hill island geology. At 4000 m, borehole DGU no. 159.983 describes clay from elevation +10 to -5 m with a description that could indicate an interglacial origin. The clay is described as being firm and containing gyttja (Eem age?). The tTEM data shows relatively low resistivities, which corresponds quite well to a possibly marine clay.

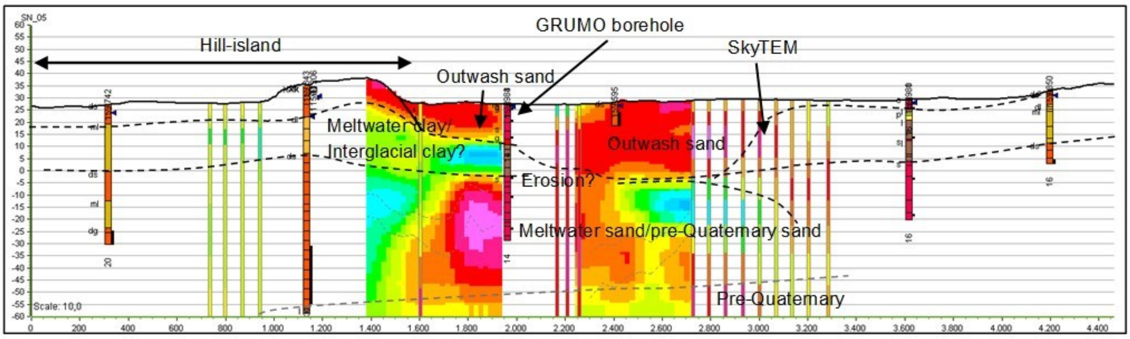


Figure 5.12: Cross-section SN_05, S-N. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

Cross-section SN_05 (Figure 5.12) crosses the study area from south to north in the central part. At 2000 m, the above-mentioned borehole DGU no. 159.983 is shown. SkyTEM data north of the tTEM survey shows the same pattern as the tTEM going from high resistivities (outwash sands) to moderate to low resistivities (20-40 Ohmm). North of the study area, the clay layer seems to be situated at lower elevations (below -20 m).

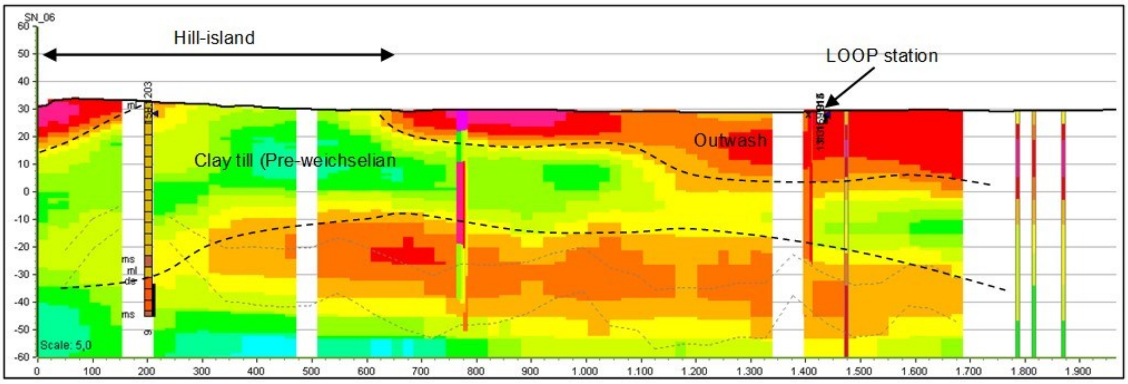


Figure 5.13: Cross-section SN_06, S-N. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

Cross-section SN_06 (Figure 5.13) is oriented South-North about 1 km east of SN_05. Here the hill island area is dominated by moderate resistivities (30-50 Ohmm) which fits well with clay till found in borehole DGU no. 159.203. The borehole describes clay till from the surface to a depth of 56 m. TTEM data to the north indicate a thinner clay layer below the outwash sands.

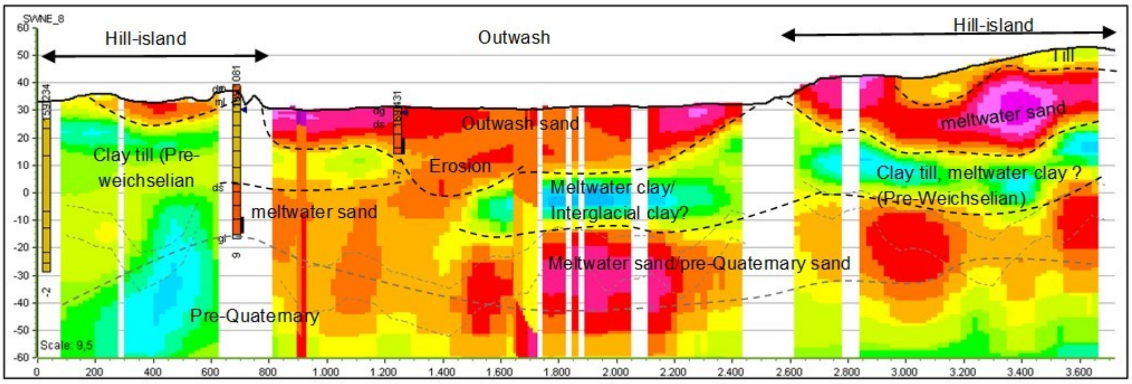


Figure 5.14: Cross-section SWNE_8, SW-NE. For location, see Figure 5.7. TTEM data are shown as a 3D resistivity grid and SkyTEM data are visualized as single sounding poles.

Cross-section SWNE_8 (Figure 5.14) strikes SW-NE through the eastern part of the study area and illustrates the geological changes going from hill island to outwash plain and then again up on the Toftlund hill-sland to the north. TTEM data indicate possible erosion in the deeper part of the outwash plain; see profile at 1200 m to 1800 m. The western parts of the hill-island area show a thick succession of clay till; see 0-500 m (as shown on SN_06). Borehole DGU no. 159.1081 terminates in Miocene mica clay, but it is difficult to conclude if this is the actual boundary between the Quaternary and the Miocene successions or maybe disturbed layers from earlier glaciations (Saale or earlier).

Overall, LOOP 6 comprises the following geological characteristics:

a) Outwash plain geology of Late Weichselian age with occurrences of Postglacial deposits in low-lying areas.
b) A pre-Weichselian glacial landscape affected by glaciers during the Saalian glaciation (or earlier). Sediments are clay tills, meltwater clays and meltwater sands.
   - I. Upper till deposits on hill-islands
   - II. Meltwater sand on hill-islands
   - III. Fine-grained sequences of meltwater clay, clay till and possible interglacial clays mapped beneath the outwash sands and as deeper parts of the hill-islands
c) Deeper successions of Quaternary deposits with a transition to the Miocene formations. A complex geological setting which is difficult to resolve from the datasets. The succession is presumably disturbed by deep faults, glacial erosion and glacial deformation.

Glaciotectonically deformed sediments are widespread in the region (e.g. Houmark-Nielsen 2007; Jørgensen et al. 2015). The LOOP-area has not been overridden by glaciers during the Weichselian meaning that the deformations of the sedimentary succession most likely can be related to the Saalian glaciation. The tTEM reveals that the meltwater sediments above the clay in the hill islands are deformed as well. The Saalian clays have also been eroded locally, which means that the clay can be considered as discontinuous and having a highly varied thickness throughout the area. The tTEM does not map the deep parts of the succession, but the highly irregular bottom surface of the Saalian clays points to an equally deformed succession at depth. This is supported by findings of isolated layers of Miocene sediments within the Quaternary succession.

It is possible that interglacial marine clays are present in the area. These deposits would be expected in former low-lying areas during the Holsteinian or Eemian interglacials. A few kilometers west of the study area (near Løgumkloster) a sequence of interglacial clays is described in boreholes (e.g. DGU nr. 159.1254, see Sandersen and Jørgensen 2016). The interglacial deposits are found at approx. elevation -10 to -25 m.

Studies of the outwash plain topography at Løgumkloster to the west and Tinglev to the south propose neotectonic deformation of the sedimentary succession due to fault reactivation connected with glacio-isostatic rebound (Sandersen and Jørgensen, 2015). With a location close to Tinglev and Løgumkloster, the same could be the case in the Bolbro LOOP area. However, the interpretations in the study area have not found firm indications pointing to this type of deformation.

5.6 Characterizing geological elements

To summarize the interpretations, the geological elements characterizing the LOOP 6 area have been outlined. The delineated elements are sketched in Figure 5.15 and comprise the following:

- **GE1**: Deeper successions of Quaternary deposits and Miocene formations
- **GE2**: A pre-Weichselian glacial landscape affected by glaciers during the Saalian glaciation (or earlier). Sediments are clay tills, meltwater clays and meltwater sands
- **GE3**: Outwash plain geology of Late Weichselian age with occurrences of postglacial deposits in low-lying areas

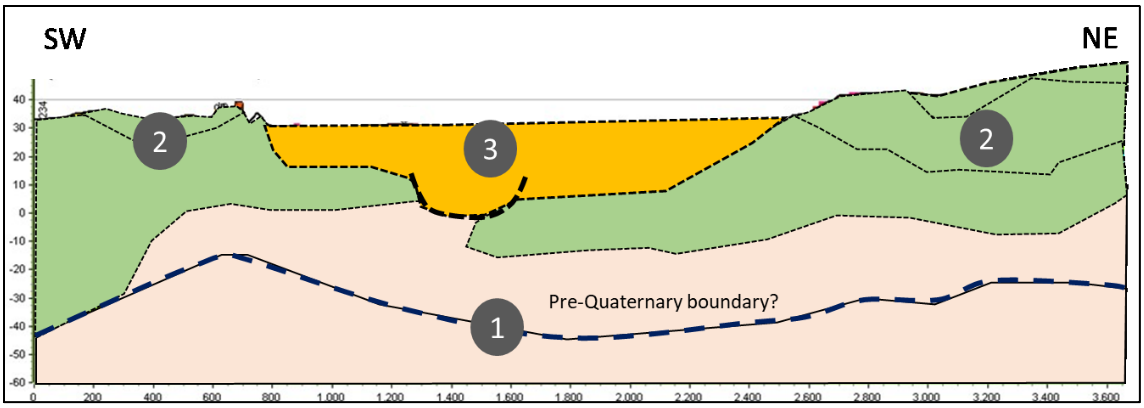


Figure 5.15: Illustration of identified geological elements in the LOOP 6 area.

5.7 Summary and conclusions

- **Geophysical mapping:** The area has a good but patchy coverage with geophysical data. The tTEM data has greatly improved the understanding of the geological setting. The tTEM provides a better resolution compared to the existing SkyTEM soundings, but the small SkyTEM survey in the area has been useful in the interpretation by adding information below the tTEM DOI.

- **Borehole information:** The information from boreholes is limited as many of the boreholes are shallow, but the general perception of the upper succession is good. The top of the pre-Quaternary sequence is only penetrated by a few boreholes and therefore the boundary to the Miocene is difficult to map.

- **Geological setting:** The study area is predominantly defined by a Late Weichselian outwash plain with occurrences of Postglacial deposits in low-lying areas. The lower boundary of the outwash plain sediments is a pre-Weichselian glacial landscape affected by glaciers related to the Saalian glaciation and/or earlier glaciations. Sediments are clay tills, meltwater clays and meltwater sands. The older glacial elements are visible in the topography as "hill-islands". The deeper succession of Quaternary deposits and the boundary to the Miocene formations are more complicated to interpret from the few deep boreholes and the geophysical datasets. It is likely though, that glacial erosion and deformation has disturbed the pre-Weichselian succession.

- **Geological interpretation and correlation:** The interpretations of the data have revealed a good correlation between the terrain and the subsurface structures. The outwash plain can be distinguished from the older glacial geology, and the observations fit well into the current knowledge of the latest geological events in the area. A detailed understanding of the geology in the deeper parts is difficult to obtain because of sparse data.

6. MapField demo sites – Hulebro Bæk and Hagens Møllebæk, Salling

6.1 Geomorphology and surface geology

The Mapfield demo sites, Hulebro Bæk (1) and Hagens Møllebæk (2) are located on the Salling peninsula in the north-western part of Jutland (Figure 1.1) in a clay-dominated moraine landscape from the last glaciation (Weichselian), see Figure 6.1, left. The Main Ice Advance in the Weichselian was from a north/north-easterly direction and especially in the northern part of Salling, ice marginal hills are visible in the terrain. At the city of Skive, just south of demo site 2, there is a transition from a moraine landscape to a younger, low-lying outwash plain surrounding remnants of glacial hills and with imprints of dead ice (Smed 1979).

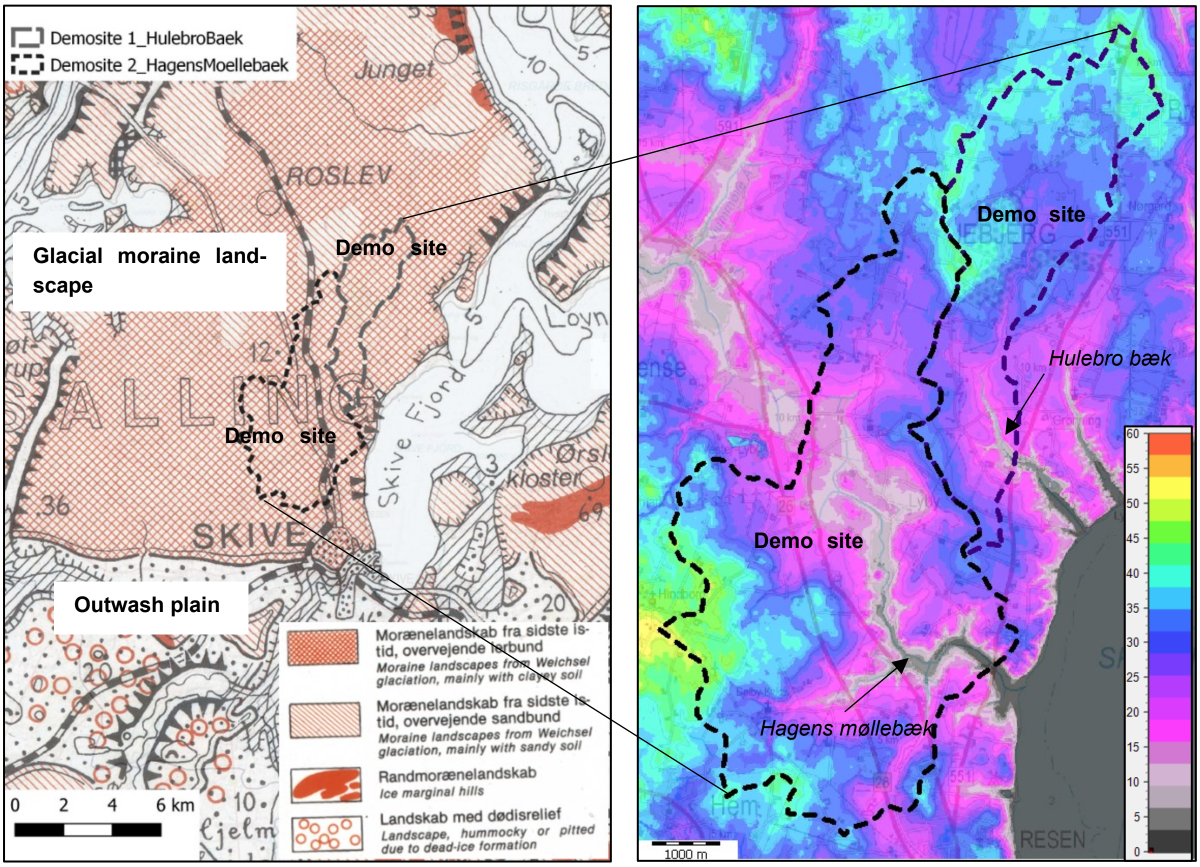


*Figure 6.1: **Left**: Map of regional surface geomorphology of Demo site 1 and 2. The two demo sites are marked with dashed polygons. They are both located on a clay-dominated moraine landscape from the last glaciation (Weichselian) (Smed 1979). **Right**: Digital elevation model (highest elevations: green, lowest: grey-black). Legend (m) in upper right corner.*

The topography in the demo site 1 is highest in the north to north-western part with elevations up to 45 m a.s.l., while the highest topography in demo site 2 is the western part with elevations up to 40-50 m a.s.l., see Figure 6.1, right. These glacial hills show no clear orientation, but north of the demo site the landscape show influence from the underlying Batum salt diapir (Grontmij 2010). The brook Hulebro Bæk cuts through the terrain with a north-south/south-east orientation in the central part of demo site 1 going towards the Skive Fjord at Lyby. A parallel erosional valley is found 500 m north of Hulebro Bæk. In the central part of demo site 2 the elevation is around 20 m a.s.l. and sloping towards the erosional lows in the terrain where the brook Hagens Møllebæk is located (elevations ca. < 10 m a.s.l.). Hagens Møllebæk turns from a N-S orientation to a W-E orientation with outlet in Skive Fjord. Several smaller brook branches are connecting to the main brook within the catchment (demo site 2).

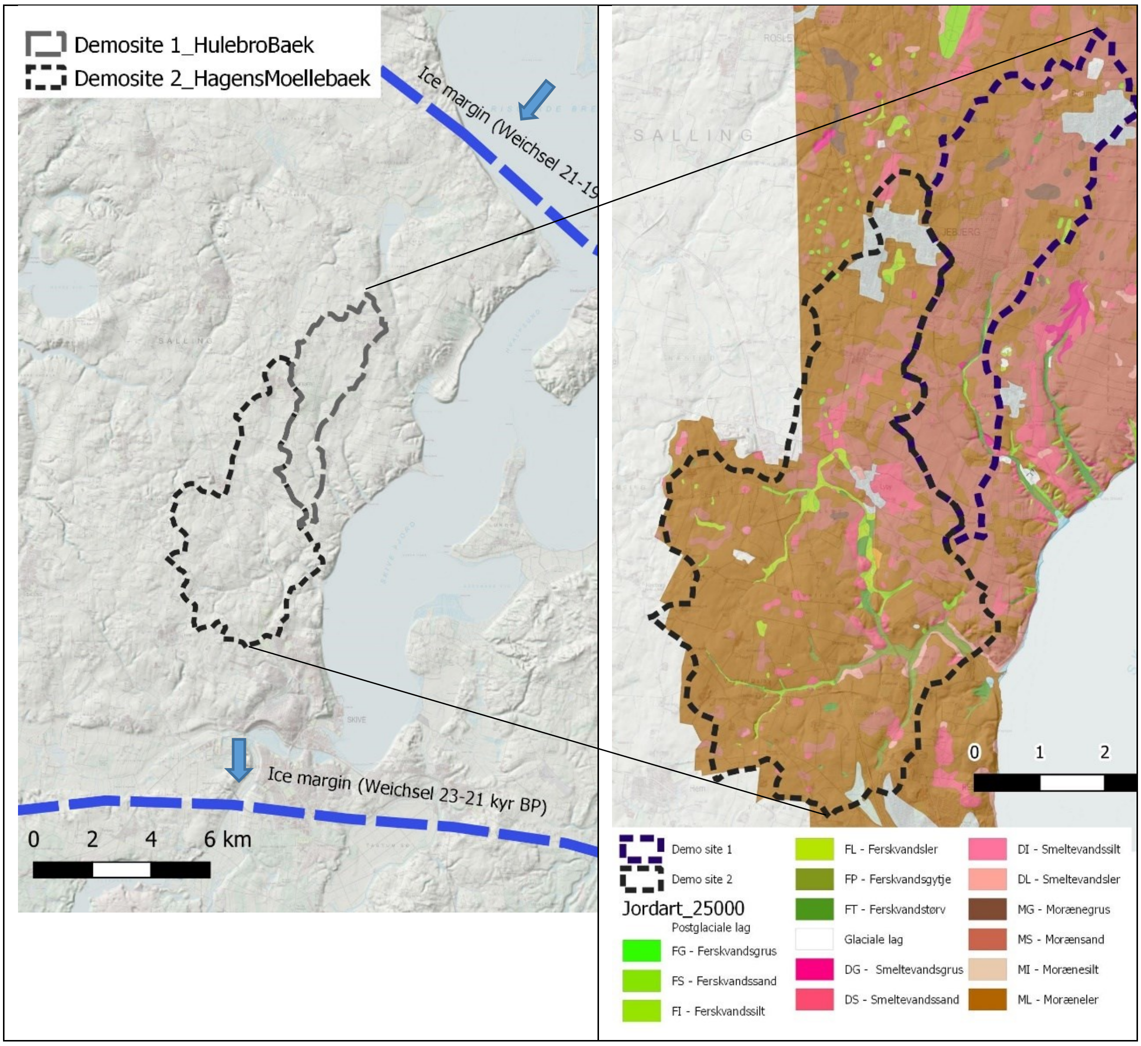
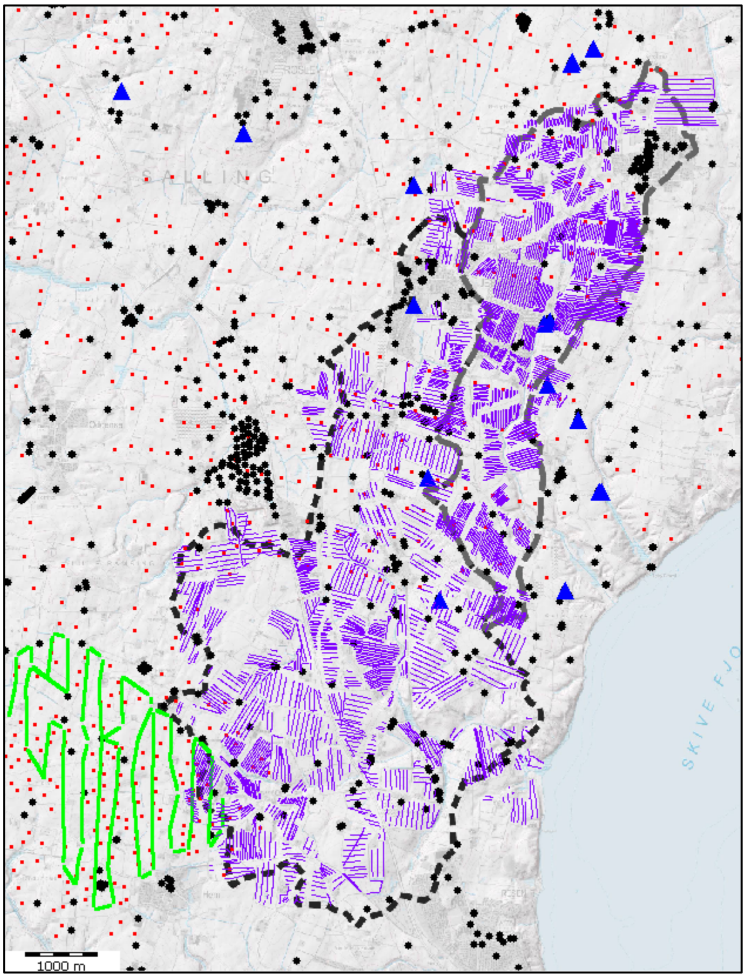


*Figure 6.2: **Left**: Illustration of known ice margins during the Late Weichselian with ice push from north and northeast (Schack Pedersen, 1995). **Right**: Surface geology map (1:25.000) describing sediment types in the uppermost meter (Jakobsen & Tougaard 2020). Brown colours: Tills; Red: Meltwater sand; Green: Post-glacial freshwater deposits (gyttja and clay).*

Figure 6.2, left, shows the extent of the former ice margins during the Late Weichselian. In the period where the ice margin was located at Skive (23-21 kyr BP), the push direction came from north. Later on, the glaciers melted back, and a younger, stagnant ice margin was located in the northern part of Salling, where the Batum salt diapir likely acted as a southern threshold (21-19 kyr BP; Houmark-Nielsen 2005, Madirazza 1979).

A map of the surface geology (the uppermost meter) is shown on Figure 6.2, right. Glacial tills are dominating the demo sites – both clay tills and sandy tills. Also, local occurrences of gravel tills are found. Postglacial freshwater deposits are found locally in topographic lows and in areas around Hulebro Brook and Hagensmølle Brook. Meltwater sand deposits at the surface are mostly described around Lyby in the northern part of demo site 2.



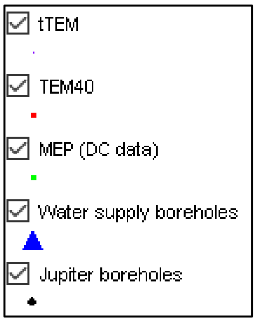


Figure 6.3: Boreholes (Jupiter database) and geophysical datasets (Gerda database) in the area. Legend is shown to the right. Demo site 1: grey polylines. Demo site 2: black polylines.

6.2 Geophysical data and boreholes

Three types of geophysical data have been collected in and around the two demo sites (see Figure 6.3):

New data collected in MapField:

- tTEM data with a total of 730 line km and a line spacing of 25 m in the northern part and 50-60 m in the southern part (tTEM; shown as purple dots) (Aarhus University 2021)

Existing data:

- TEM40 data (ground-based Transient Electro Magnetic soundings) shown as red points
- MEP data (Multi Electrode Profiling) shown as green triangles/lines
- The geological data comprise boreholes from the Jupiter database (black dots)

As part of the national groundwater mapping, several ground based TEM40 soundings have been acquired during the last 15 years. TEM40 data add information to the tTEM data and are located in mostly W-E transects with 200-500 m between the soundings. Almost all of demo site 1 is covered by TEM40, whereas no TEM40 data is collected in the central and southern part of demo site 2.

The tTEM data collected in the two demo sites differ in line spacing. Within demo site 1 (Hulebro bæk) the line spacing between soundings is 20-30 m, whereas the line spacing in the large demo site 2 (Hagens Møllebæk) is between 40-60 m. The MEP data has only been partly used in the interpretation, mainly because the data are located outside demo site 2 to the southwest (see Figure 6.3). Due to limited field access during the first field campaign, a second field campaign with additional data collection was carried out in autumn 2020. Figure 6.3 shows the total available tTEM soundings after the geophysical data processing.

The boreholes in the demo sites are mostly shallow but some deep water supply boreholes are found in the buried valley systems.

6.3 Stratigraphy

Pre-Quaternary

From a regional perspective, the subsurface in Salling is strongly affected by both doming salt diapirs and deep-seated faults. A NNE to SSW oriented fault system is found in the area (Figure 6.4, left) and this is likely to have influenced the orientation of older buried valley systems (see section 6.4 on buried valleys). Upward movement of the Batum salt diapir in the northern part of Salling, see (Figure 6.4, right), have had the consequence that old chalk deposits (Skrivekridt) have been pushed upwards to the terrain surface and layers close to the diapir were deformed. Erosion of geological layers younger than the chalk deposits is also a consequence of the upward movement of the diapir.

Figure 6.5 shows a conceptual cross-section though the Batum diapir from south to north. The demo sites are located close to ‘A’ on the profile, south of the diapir, and the profile shows that the Tertiary layers in the upper subsurface dips towards south. Studies from Batum suggest that the rising diapir posed a barrier for the forward moving glaciers during the Weichselian Glaciation, and thereby creating heavy glaciotectonic deformation north of the diapir, e.g. at the island of Fur (Madirazza 1978). South of the Batum diapir towards the demo sites, the glaciotectonics seem less intense and not obvious in the topography.

The top of the pre-Quaternary succession in the demo sites is represented by Oligocene to Miocene deposits found in boreholes and described in outcrops in e.g. Lyby east of the demo sites (Rasmussen 2009). Generally, the central and northern part of Salling is dominated by Oligocene clays, whereas the southwestern part of Salling also include Miocene mica sand and mica silt (Vejle Fjord, Billund and Klintinghoved Formations, Rasmussen et al., 2010). It is expected that the Oligocene clays will stand out as layers of very low resistivity in the tTEM survey, whereas the rather thin sequences of mica sand or silt will be more difficult to distinguish in the geophysical data. At the Lyby coastline (east of the demo sites), outcrops show a regional gravel layer, indicating the boundary between the Billund Formation and the Klintinghoved Formation. Based on Rasmussen (2009), it is likely that findings of pre-Quaternary sand in the study sites can be correlated to the Hvidbjerg Member. Towards north, clays from the Brejning Formation are expected.

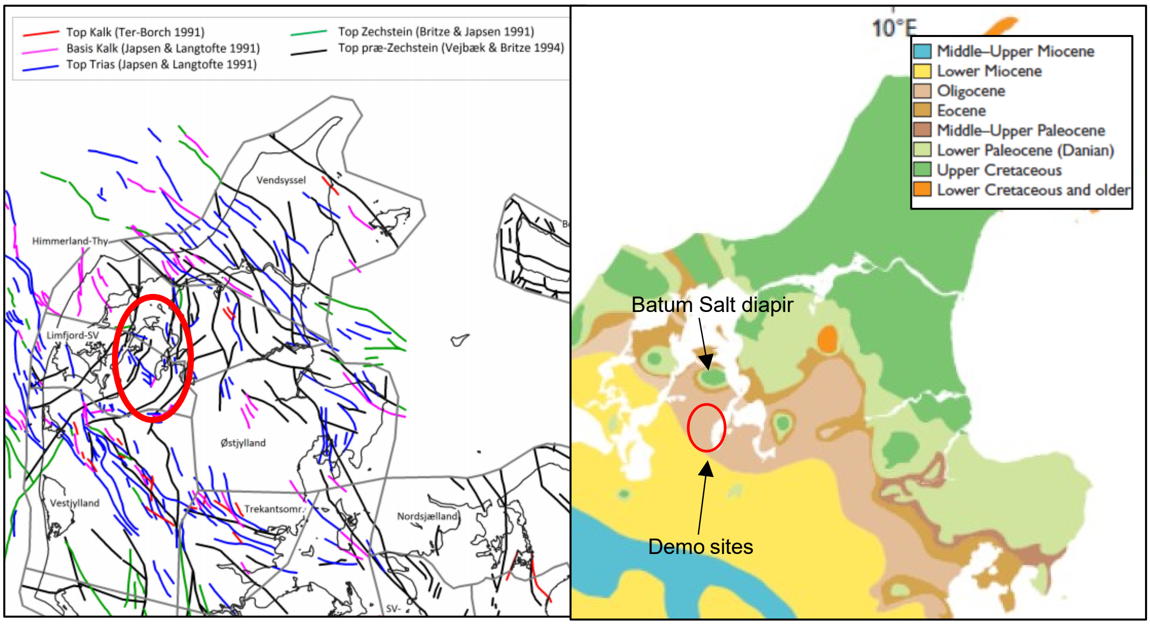


*Figure 6.4: **Left**: Deep-seated fault lines in Denmark (from Sandersen & Jørgensen, 2016), red circle: Location of demo sites. **Right**: Pre-Quaternary surface of the northern part of Jutland (from Rasmussen et al. 2010). Red circle: location of demo sites. The Batum salt diapir is marked with an arrow.*

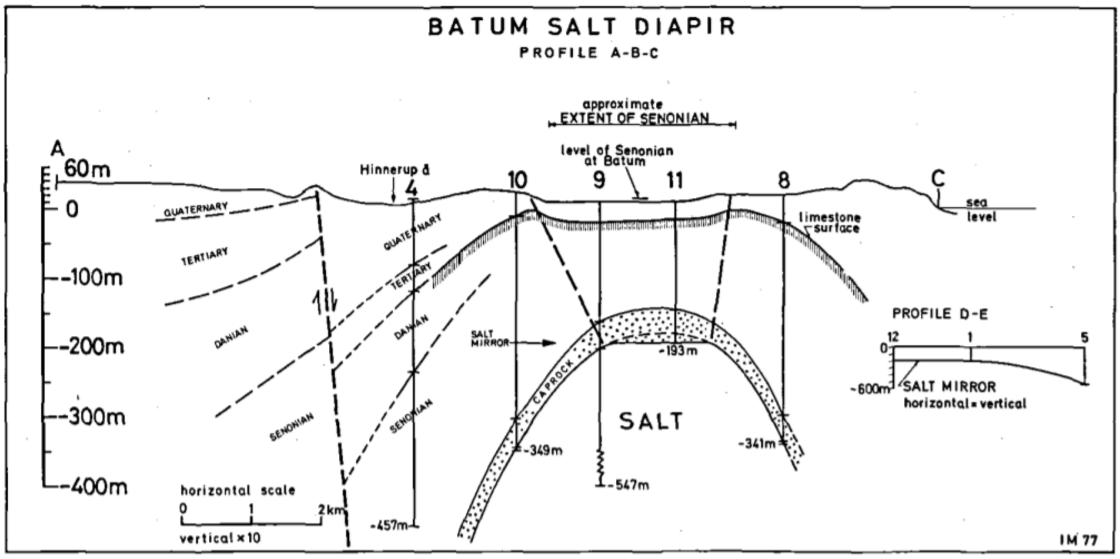
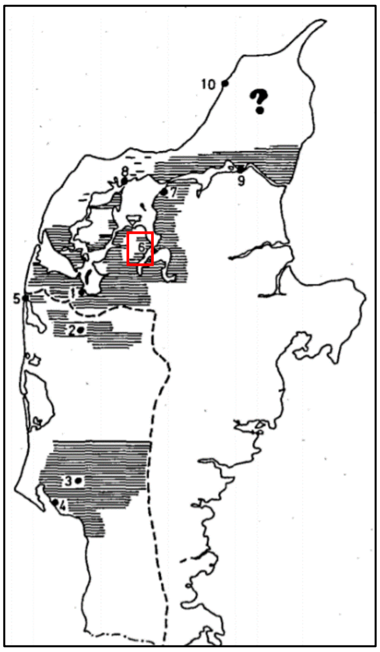


Figure 6.5: Sketched South (A) - North (B) profile across the Batum salt diapir illustrating the displacement of the surrounding deposits. The interpretation of fault lines is based on the deep boreholes (numbered vertical lines) in the area (Madirazza 1978).

The Quaternary

The Quaternary succession consists of clayey and sandy tills, meltwater sand and clay, and possibly also interglacial deposits. The Quaternary succession varies in thickness from less than 10 m up to more than 120 m in buried valley structures. Many ice advances have covered Salling resulting in a complex Quaternary stratigraphy (Houmark-Nielsen, 2005). The smooth, hilly topography of the demo sites show no obvious signs of large-scale glaciotectonics (see Figure 6.2).



Studies by Jensen (1984) has documented the presence of a widespread layer of meltwater clay in Western and Northern Jutland, interpreted to have a Late-Elsterian age (Figure 6.6). The clay layer is described at locations close to the demo sites, which makes it likely that it can be found within the demo sites as well, see Figure 6.6. A large lacustrine and possibly later marine environment covering the Limfjord area was present at the end of the Elsterian glaciation and in the Holstein interglacial (Jensen 1984). Based on this, glacial deposits from both the Elsterian, Saalian and Weichselian glaciations are likely to be found in Salling, and Quaternary deposits above the Late-Elsterian clay would therefore be of Saalian or Weichselian age. The physical impact on the clay by the glaciers during the Saalian and Weichselian has been plastic deformation of this Late-Elsterian clay – more or less extensively.

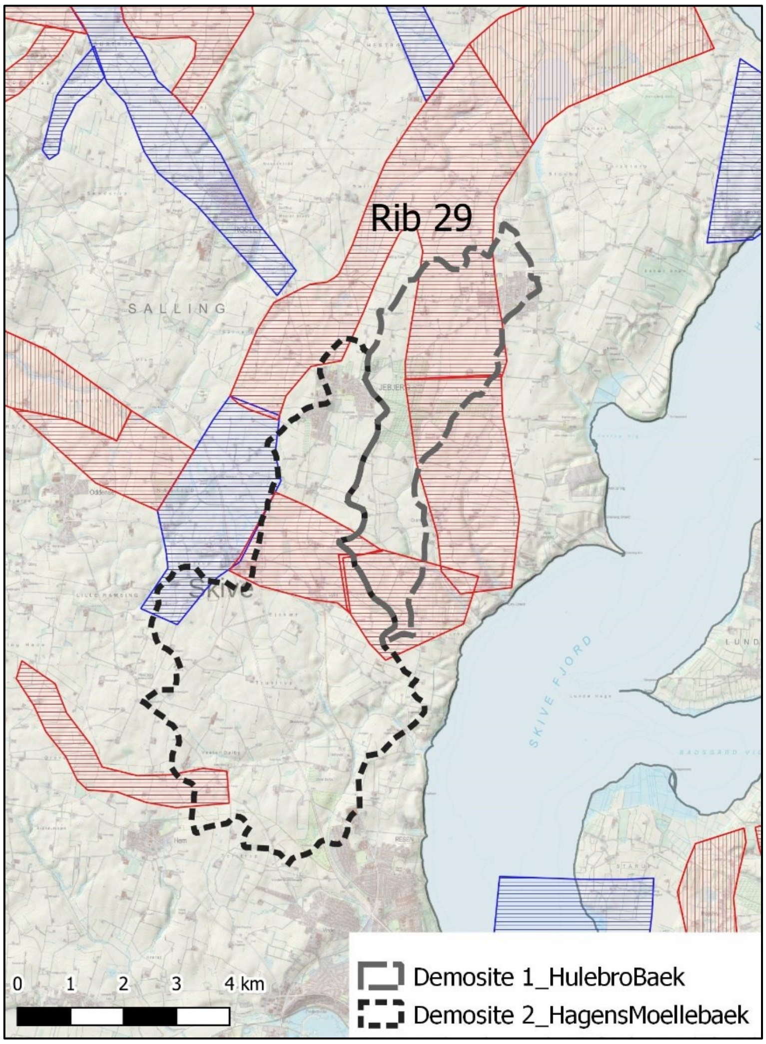
Figure 6.6: Interpreted distribution of regional late Elsterian to Holsteinian meltwater clays analyzed at different locations. From Jensen (1984). The Salling area is marked with a red rectangle.

6.4 Buried tunnel valleys

The Salling peninsula is crosscut by several buried valleys with different orientations and age. Figure 6.7 shows the buried valleys mapped within the two demo sites based on existing TEM40 soundings from the national groundwater mapping and boreholes (Sandersen & Jørgensen 2016). The buried valleys were formed as tunnel valleys underneath the ice sheets during the Quaternary.

The large, buried valley system (RIB29) comprise two broad valleys with a N-S and NNE-SSW orientation and possibly an older valley generation with a WNW – ESE orientation. The valleys are eroded into Oligocene-Miocene clays at elevations down to -100 to -150 m a.s.l. To the north, the valley bottom consists of Danian limestone due to uplift caused by the Batum salt diapir. The valley infill is described in boreholes as varying series of clay till, meltwater sand and meltwater clays (Sandersen & Jørgensen 2016).

Within the demo sites, all valleys are completely buried and not visible in the landscape, but it is interesting that many of the brooks and creeks have the same orientations as the valley systems.



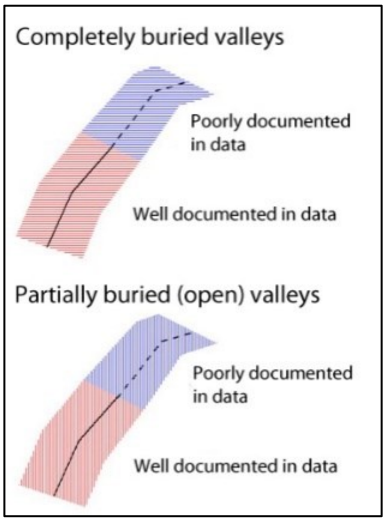


Figure 6.7: Mapped buried valleys close to the study area (shown with black hatched line). Legend for the map is shown above (Sandersen & Jørgensen, 2016; www.buriedvalleys.dk).

6.5 Geological interpretation of geophysical data (both demo sites)

Demo site 1 and 2 are described jointly in the following geological interpretations because the areas are located next to each other in the same geological setting. This also provides the best regional understanding of the subsurface because some buried valleys, for instance, cross both study areas.

The total tTEM coverage in the demo sites is good (keeping in mind that most parts of demo site 2 is mapped with a larger line spacing, 40-50 m), see Figure 6.3. Ground based TEM40 soundings are present in most of demo site 1, but only in a smaller part of demo site 2. The TEM40 soundings are valuable in combined interpretations with tTEM and for providing information about the deeper parts such as the mapped buried valley systems. MEP data (west of demo site 2) are included but less useful in the interpretation, because the tTEM data provides a better resolution.

Cross-sections through the tTEM and TEM40 soundings are shown on Figure 6.8 and described in the following. TEM40 data is visualised as single sounding poles on the cross-sections, while the tTEM smooth models are shown as a 3D resistivity grid with a 25 x 25 x 1 m discretization.

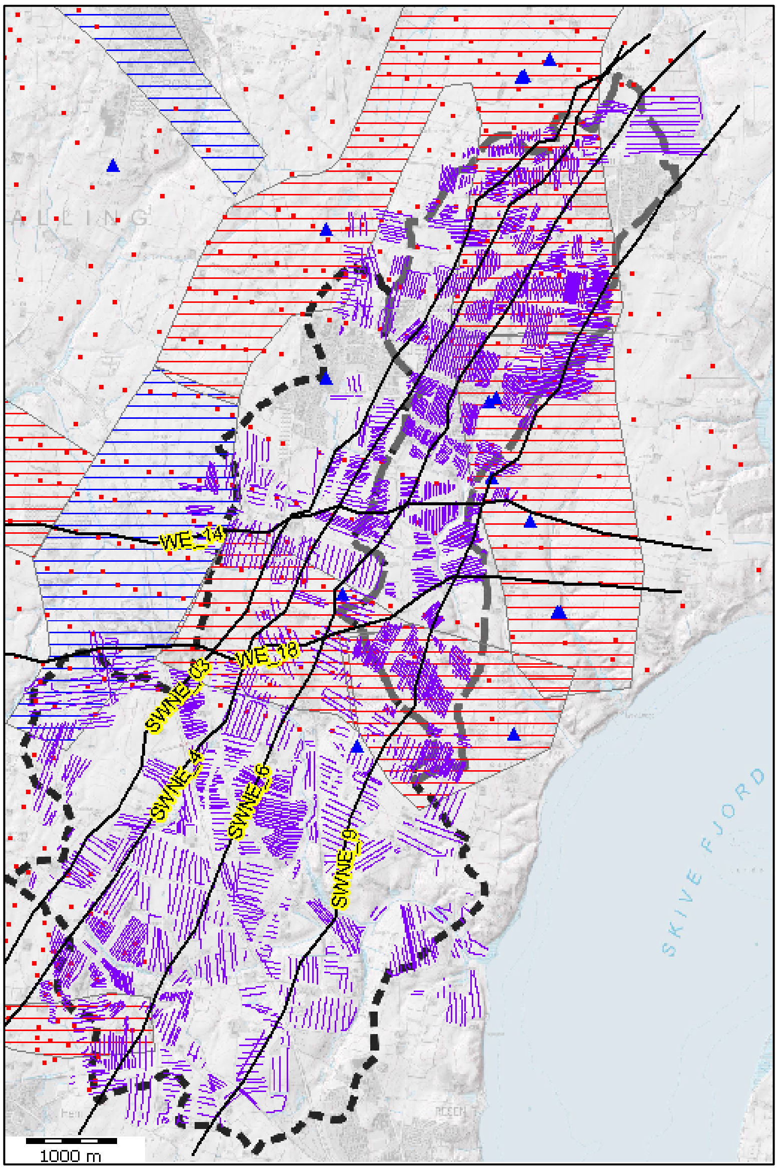


Figure 6.8: Cross-section overview: Black lines with yellow labels. Red and blue shaded polygons represent mapped buried valleys (see Figure 6.7; Sandersen & Jørgensen, 2016). Purple points: tTEM data, red points: TEM40 soundings, Water supply wells: blue triangles.

In the following, the geological interpretations performed on the cross-sections (shown in Figure 6.8) and on four selected 2D resistivity maps are presented (Figure 6.9 and Figure 6.10). The Depth of Investigation (DOI) for the tTEM data is shown on the cross-sections with thin, dashed grey lines in Figure 6.11-6.16.

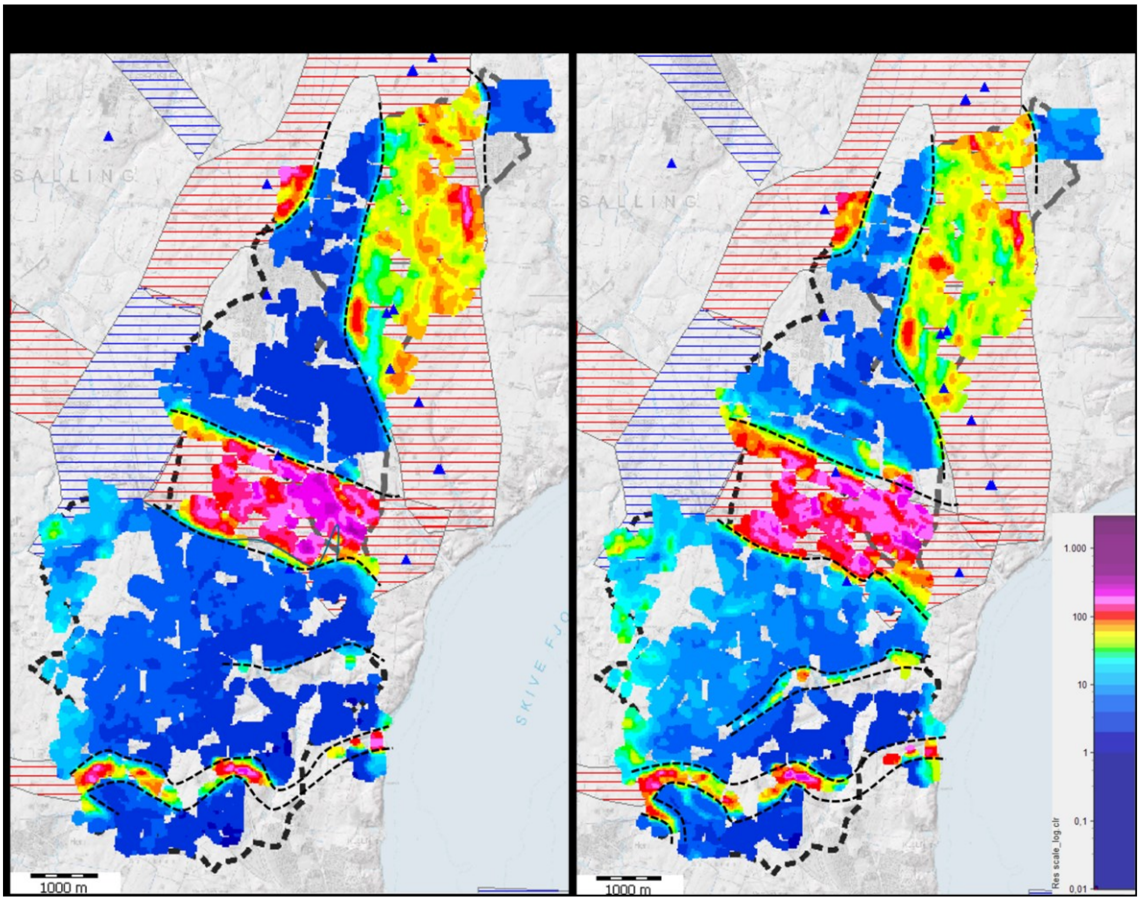


Figure 6.9: Interpolated resistivity slices (Grid cells 25x25x1 m) for elevation -20 m a.s.l. and -10 m a.s.l. Thin dashed lines indicate buried valleys interpreted from tTEM data. Blue colours represent clays and red colours indicate sand to gravel. Red and blue shaded polygons represent mapped buried valleys (see Figure 6.7; Sandersen & Jørgensen, 2016).

Figure 6.9 shows two slices of tTEM 3D resistivity grids with an underlying theme of earlier mapped buried valleys. The slices give an overview of the resistivity contrasts of conductive pre-Quaternary clays (blue) and different generations of incised buried Quaternary valley systems. The resistivity variations within the valleys indicate different types of infill sediments. For instance, the N-S oriented valley shows high and moderate resistivities indicating infill of sand and clay, respectively. This is confirmed by boreholes in the valley, describing both clay till, meltwater clay and meltwater sand. In contrast to the N-S valley, the wide WNW-ESE valley that crosses parts of both demo sites, is dominated by high resistivities representing sand/gravel. At elevation -20 and -10 m a.s.l., two narrow E-W valleys are identified cross-cutting Miocene and Oligocene deposits to the south (see Figure 6.9).

Figure 6.10 gives an overview of the slices at elevation -2 m a.s.l. and +10 m a.s.l. The same large valley structures, both wider than 1500 m, are visible in these upper levels as well, where also additional shallower valleys stand out. In the large N-S valley, covering most parts of demo site 1, a narrow, internal low resistivity structure of deformed meltwater clays is identified. This meltwater clay is expected to be of Late-Elsterian age and is deformed by an eastern to north-eastern ice push.

In the northern part of demo site 2, a 700-900 m wide high resistivity valley with the general orientation SE-NW can be identified clearly on the elevation map +10 m a.s.l. On cross-sections, the buried valley appears to continue close to the surface only covered by a thin layer of clay till. Several narrow valleys (high resistivities) in a complex network are found in the southern part of demo site 2 (Figure 6.10, right). Also, these smaller valley systems can be followed close to the terrain.

On both resistivity maps on Figure 6.10, the central and western part of demo site 2 is characterized by low to moderate resistivities with no or very few cross-cutting valleys. The low to moderate resistivities are expected to represent a succession of Miocene deposits (probably mica clays and silts of the Vejle Fjord/Klintinghoved Fm) with clayey tills above.

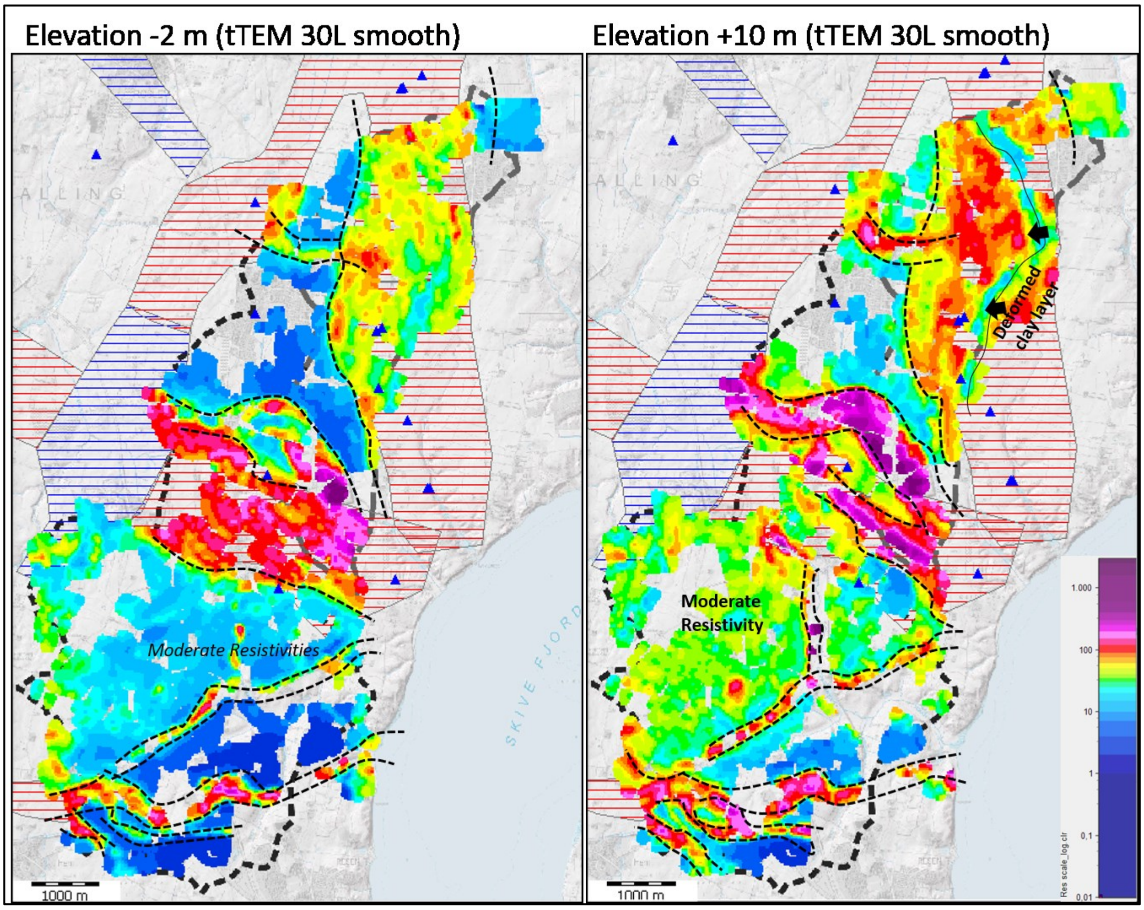


Figure 6.10: Interpolated resistivity slices (Grid cells 25x25x1 m) for elevation -2 m a.s.l. and +10 m a.s.l. Thin dashed lines indicate buried valleys interpreted from tTEM data. Red and blue shaded polygons represent mapped buried valleys (see Figure 6.7; Sandersen & Jørgensen, 2016).

Cross-section SWNE_03 (Figure 6.11) gives a SW-NE overview covering both demo sites. The boundary between the Quaternary/remnants of Miocene and the Oligocene clays stands out quite clear in the geophysical data in all of the area - going from moderate and high resistivities (Quaternary deposits and to a smaller degree Miocene deposits) to resistivities below 10 Ohmm (blue colours). As sketched on the cross-section, the large N-S oriented buried valley is seen from around the distance 11.000 m, covering demo site 1, and is eroded down to more than 150 m below surface (see borehole DGU 46.834 at distance 13.500 m).

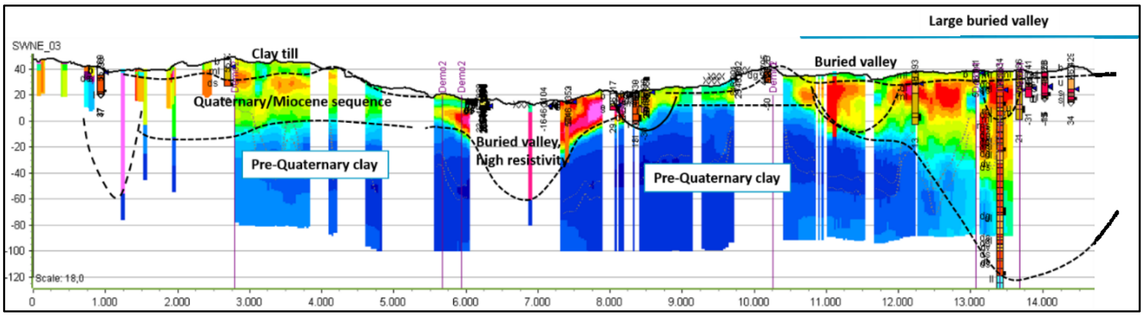


Figure 6.11. Cross-section SWNE_03, southwest to northeast. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The wide N-S buried valley is interpreted on cross-section SWNE_4 (Figure 6.12). The infill sediments vary as seen in both tTEM and boreholes, and at the distance 13.000 m, the narrow valley with infill of presumably meltwater clays can be seen between 0 and +20 m a.s.l. as low resistivities (see Figure 6.10).

At 6000-9000 m (Figure 6.12) the profile crosses the E-W oriented valley representing another generation. The valley seems to be dominated by sandy infill (high resistivities). A possibly younger valley at 8000-9000 m seems to have eroded parts of the older valley and apparently also more than 10 m into the pre-Quaternary clays.

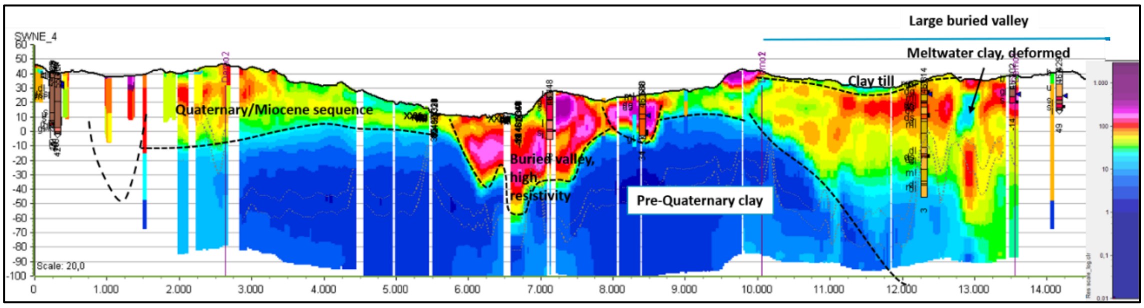


Figure 6.12: Cross-section SWNE_4, Southwest to northeast. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section in Figure 6.13 (SWNE_06) also crosses both demo sites southwest to northeast, see location on Figure 6.8. The cross-section shows somewhat the same picture as SWNE_04: a) a large buried valley to the north with a highly complex infill, b) a high-resistivity valley in the overlap area between demo site 1 and demo site 2 with an east-west orientation; c) a succession in demo site 2 to the south with clay till, sands and a system of overlapping buried valleys eroded down to elevation -40 m a.s.l. or less, and d) a lower boundary to the marine, pre-Quaternary clay.

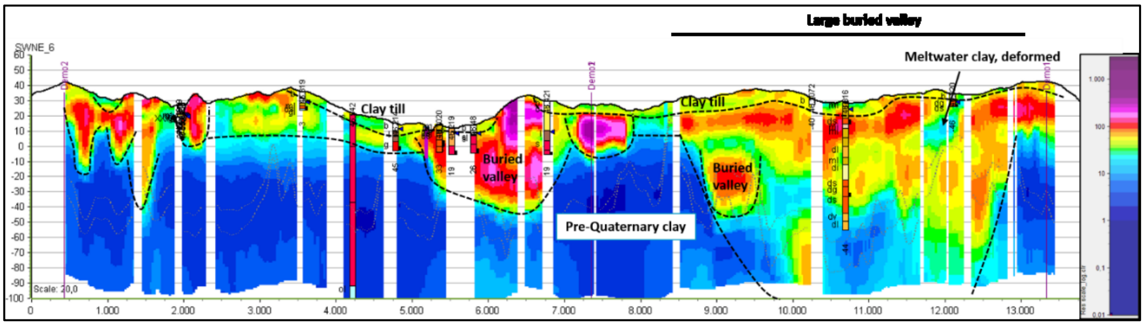


Figure 6.13: Cross-section SWNE_6, southwest to northeast. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section SWNE_9 in Figure 6.14 crosses the eastern part of demo site 1 and demo site 2 from south to north. The interpretations represent the same trends as described on the other cross-sections. In this cross-section, data indicate deformation of layers in the large northern buried valley (8500-11000 m) and in areas outside the valleys (4000-5000 m). The layers seem to have been affected by glacial push from N-NE. It is important to notice on the cross-section, that the buried valley at 7000 m close to Hulebro brook seems to have no or a very limited cover of clay till in this specific area.

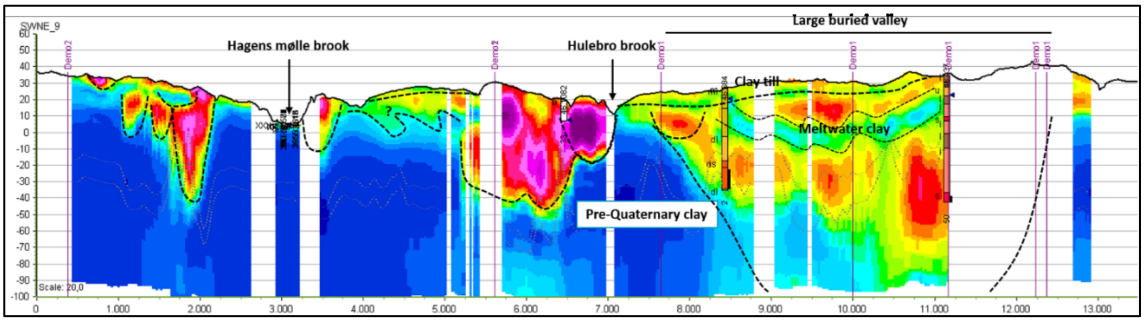


Figure 6.14: Cross-section SWNE_9, southwest to northeast. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section WE_14 (Figure 6.15) is a west-east oriented cross-section following the valley of rather high resistivities eroded down to elevation -10 to -25 m a.s.l. running through both demo site 1 and 2. At around 4000 m a cluster of boreholes show meltwater sand and gravel corresponding well to the high tTEM resistivities. The valley is in this section covered by a 5-15 m thick clay till unit, that probably was deposited by the ice covering the area 23-21 kyr ago.

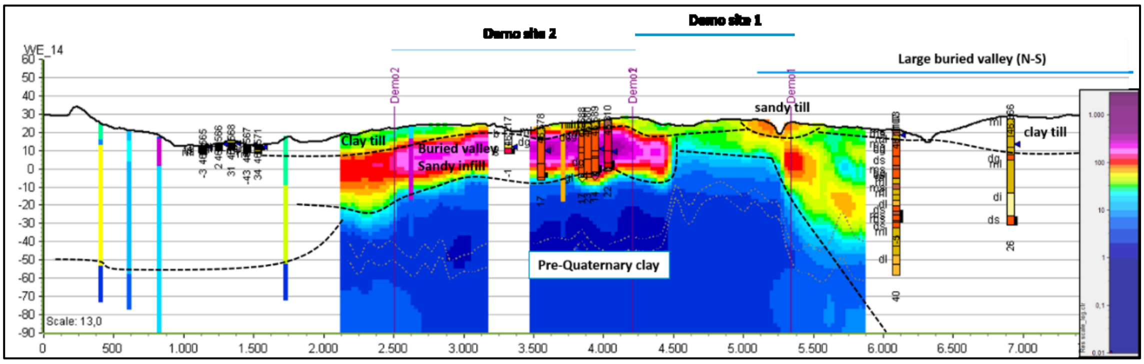


Figure 6.15: Cross-section WE_14, west to east. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section WE_18 (Figure 6.16) runs parallel and just south of WE_14 through the larger E-W buried valley. In this section, an internal clay layer (probably clay till) is identified inside the buried valley (see 3500-5000 m). At 4000-4500 and 5000-5500 the valley is cross-cut by younger buried valleys also visible primary as high-resistive, sandy infill.

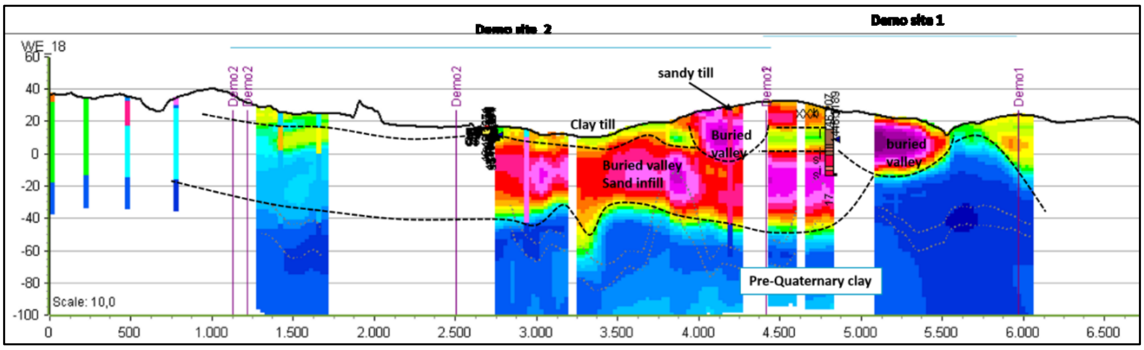


Figure 6.16: Cross-section WE_18, west to east. For location, see Figure 6.8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

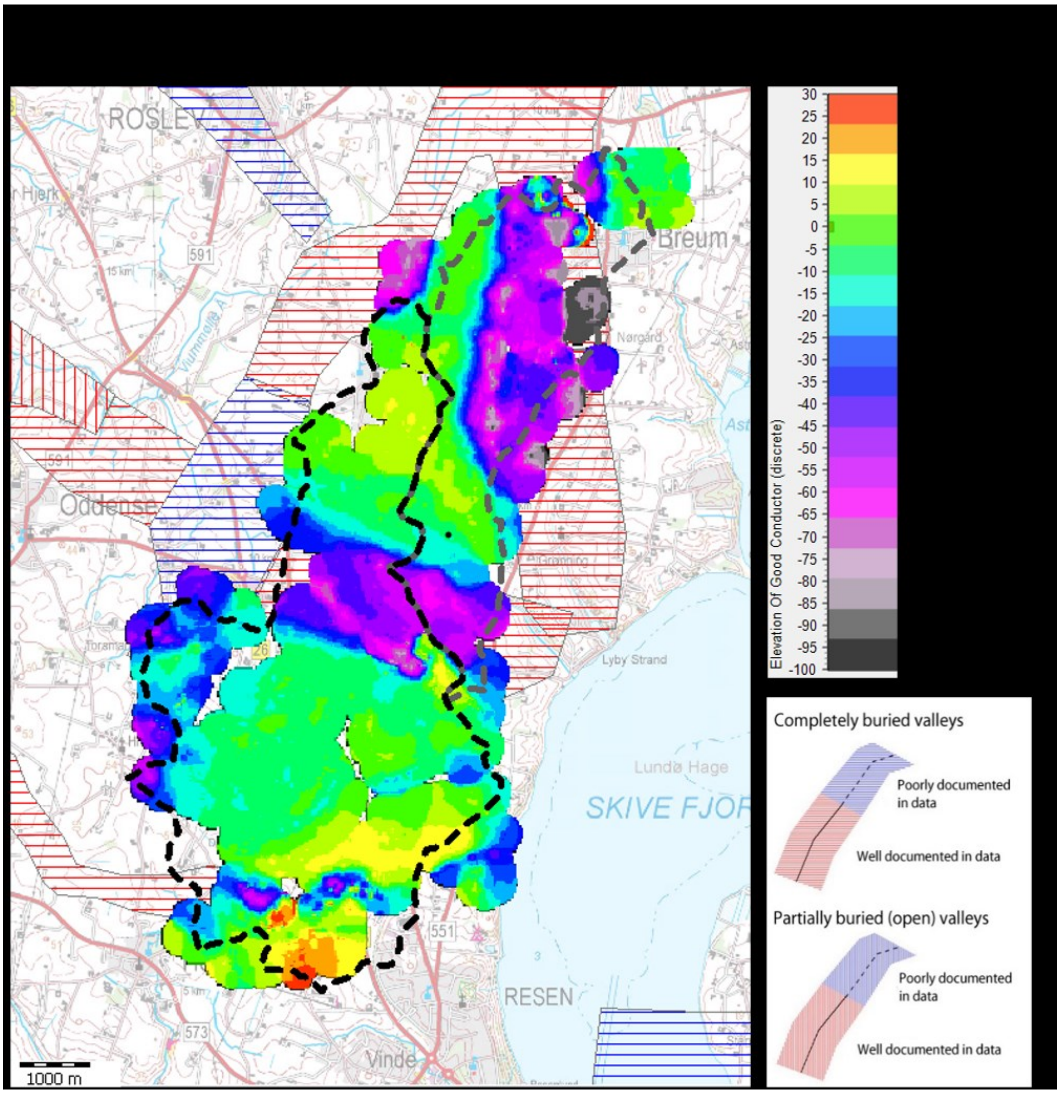


Figure 6.17: Elevation of good conductor in tTEM data. The criterion is that the deep low-resistive layer in the smooth tTEM models must be < 10 Ohmm. Red and blue shaded polygons represent mapped buried valleys (see Figure 6.7; Sandersen & Jørgensen, 2016).

Finally, on Figure 6.17 is a 2D overview of the elevation of the good conductor, which in this geological setting is interpreted as the elevation of the pre-Quaternary surface in most part of the demo sites. The interpolated surface clearly maps the deeply incised buried valleys in the tTEM covered area, whereas the shallow valleys are not visible on the map.

6.6 Characterizing geological elements

To summarize, the following four geological elements could be identified in this preliminary geological interpretation:

- **GE1: Pre-Quaternary clays (Oligocene -Miocene marine clays):** The pre-Quaternary succession characterized by Oligocene-Miocene clays. The outline of the pre-Quaternary surface is mainly interpreted using TEM and boreholes. The geological element stand out as a low resistivity volume, is well defined, and is found very close to the surface in some areas.

- **GE2: Two W-E oriented buried valleys:** GE2 comprise two W-E/WNW-ESE oriented buried valleys where the largest (c. 1500 m wide) is cross-cutting demo site 2 and the southern part of demo site 1. In the southern part of demo site 2 a buried valley with a width of 350 m, probably related to the same generation, is included in GE2. The valleys are dominated by high resistivities in the TEM models (> 100 Ohmm) and are eroded down to elevations of -40 to -50 m a.s.l.

- **GE3: N-S oriented buried valley:** A N-S oriented valley system in a large part of demo site 1. Within the large valley, the deeper parts are interpreted to have infill of meltwater sand and clay. An expected Elsterian meltwater clay layer is identified in the valley and at elevations around 0 m a.s.l. The clay unit is glaciotectonically deformed.

- **GE4: Upper sequence of glacial deposits and remnants of Miocene deposits:** An upper sequence on the pre-Quaternary plateau outside the deep incised valleys (GE2 and GE3) containing remnants of Miocene deposits (expected to be primarily mica clays), and glacial deposits consisting of both meltwater sand and clay till. The element is cross-cut by several shallow and near-surface buried valleys with high-resistivity infill. These valleys are especially found in the southern part of demo site 2, but also in demo site 1. Some of the valleys are mapped close to terrain. An upper clayey to sandy till cover is found in most parts of the demo sites

The outlined geological elements are sketched in Figure 6.18 below:

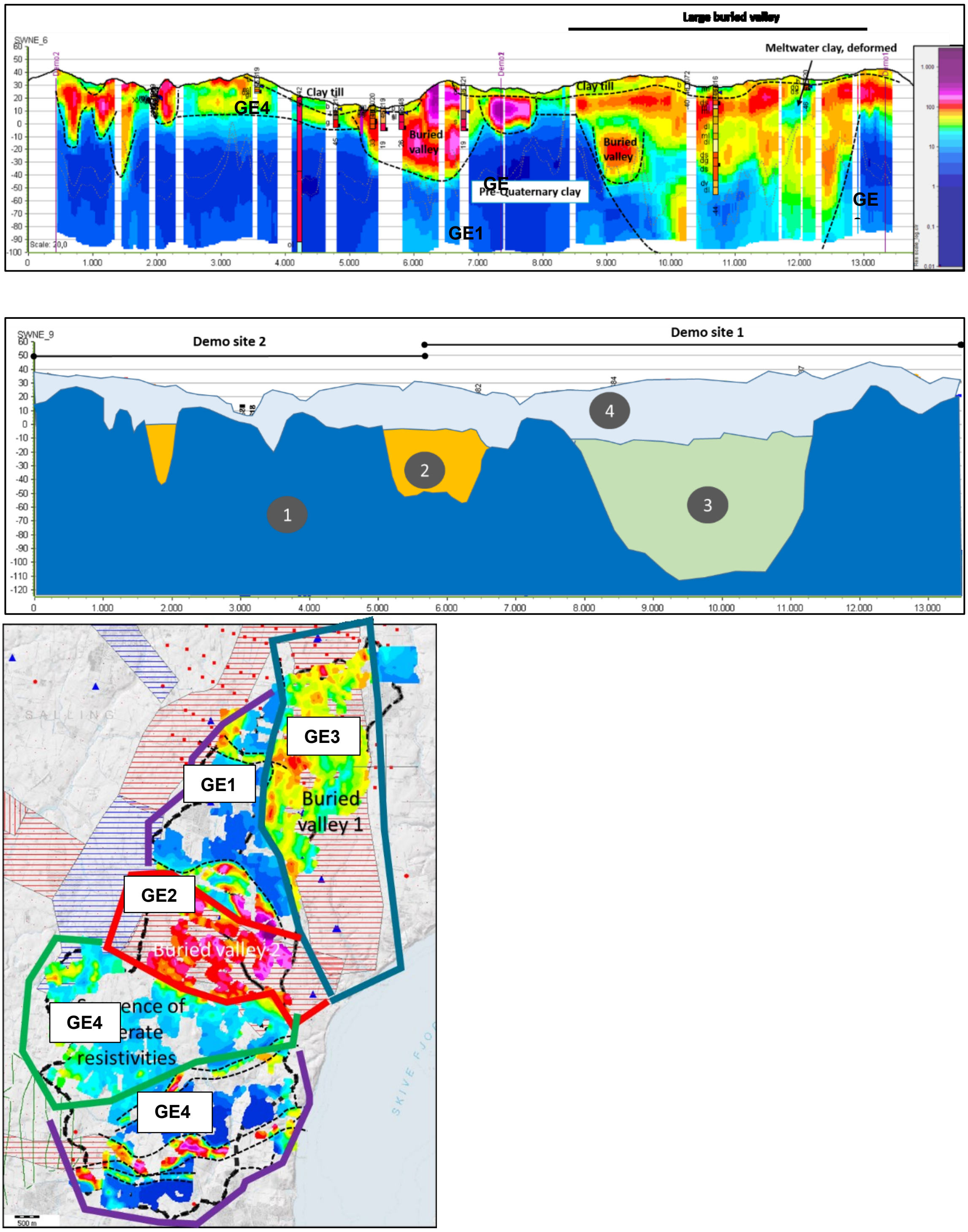


Figure 6.18: Top figures: Cross-sections showing the outlined geological elements described in the text. Bottom figure: Map view of the different geological elements dominating the two demo sites.

6.7 Summary and conclusions

- **Geophysical mapping:** The area has a good coverage with geophysical data (tTEM and ground based TEM40 soundings). The data in combination has greatly improved the understanding of the geological setting, as the single TEM40 sounding gives valuable input about the boundary of the low resistivity pre-Quaternary clays deeper than the DOI of tTEM.

- **Borehole information:** The information from deep boreholes in the buried valleys are sparse, but the general perception of the upper succession is good. The Quaternary sequence is penetrated by several boreholes outside the valleys and combined with the interpretations from geophysical data, the top of the pre-Quaternary is well defined. Because only a few boreholes are penetrating the large, buried valleys, the depth and character of the deep valley infill is uncertain.

- **Geological interpretation and correlation:** The demo sites are characterized by a clay-dominated moraine landscape from the last glaciation with occurrences of post-glacial deposits in low-lying areas. Sediments are clay tills, meltwater clays, and meltwater sands. The underlying pre-Quaternary succession is characterized by the presence of Oligocene-Miocene clays. Eroded down into these sediments are large, deep, SE-NW and N-S oriented valleys, as well as shallower and narrower valleys. The mapping of the shallow and narrow valleys has only been possible because of the tTEM survey. The pre-Quaternary surface outside the incised valleys is very shallow and the outline of the pre-Quaternary surface is interpreted using TEM and borehole data.

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