MapField – Work Package 2

Himmerland – Preliminary geological interpretations

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1 Geomorphology

The Himmerland LOOP 2 study area is located in a glacial landscape in northern Jutland just south of the city of Aars (blue polygon, Figure 1). 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 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). Streams on the outwash plain generally drains in the same direction.

The soil types in the uppermost meter of the study area are dominated by meltwater sand (red colours on Figure 3).

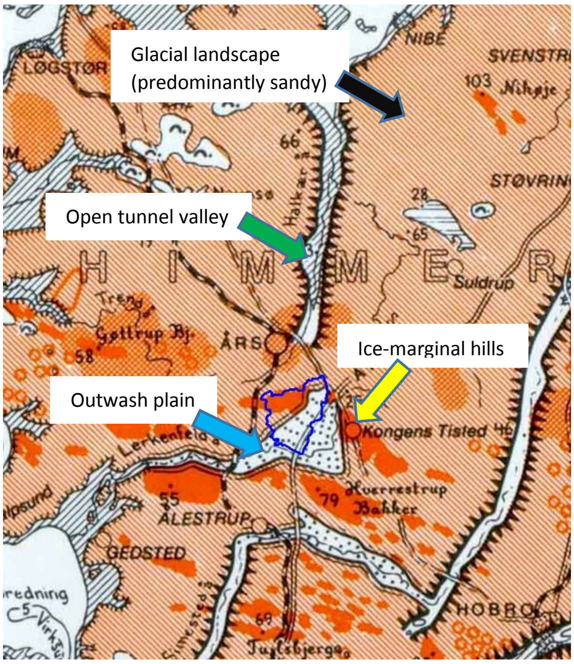


Figure 1: Geomorphological map. Blue polygon marks study area. Map width is approx. 35 km. (Map from Smed, 1979).

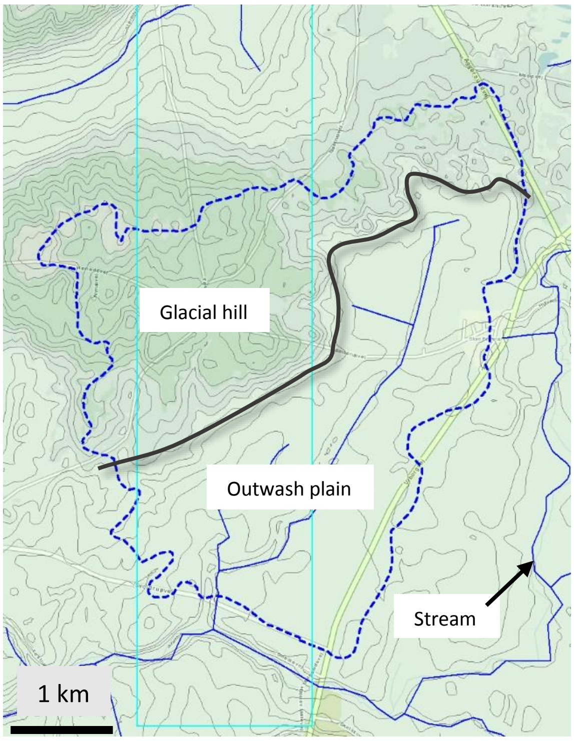


Figure 2: Main geomorphologic elements shown with elevation model (2½ m equidistance; light green: lowest elevations; darker green: highest).

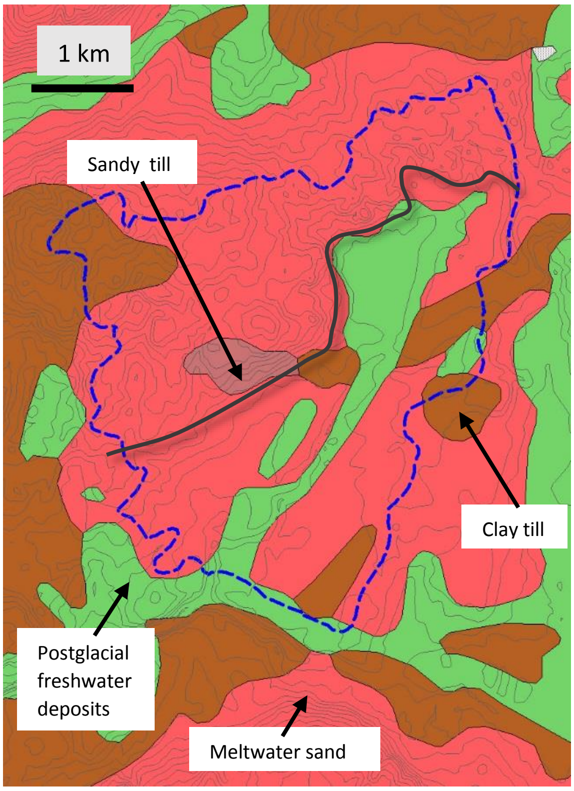


Figure 3: Soil types in the uppermost meter (Jakobsen et al. 2011). Grey line marks the boundary between the glacial hills and the outwash plain (see Figure 2)

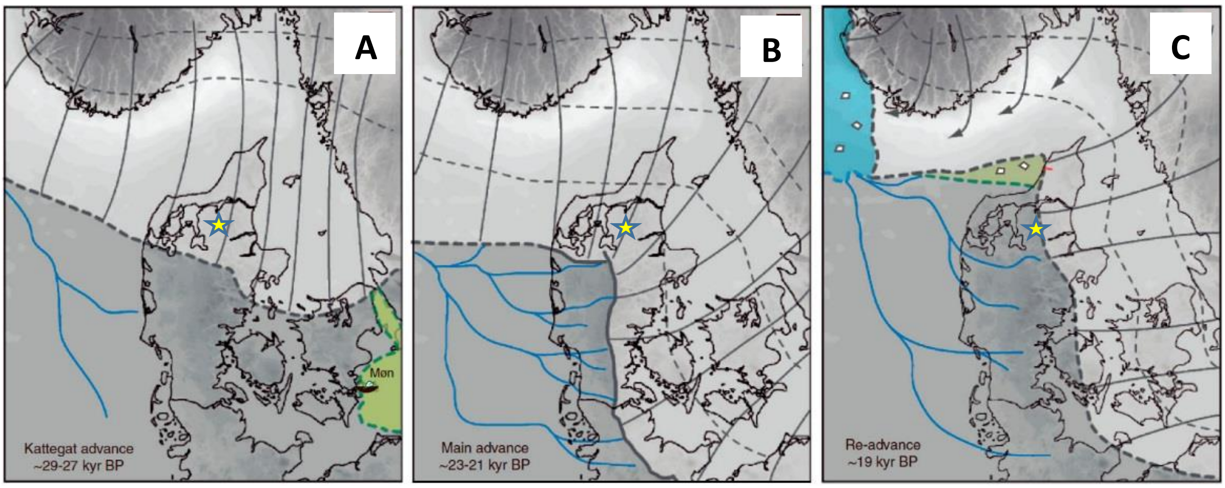
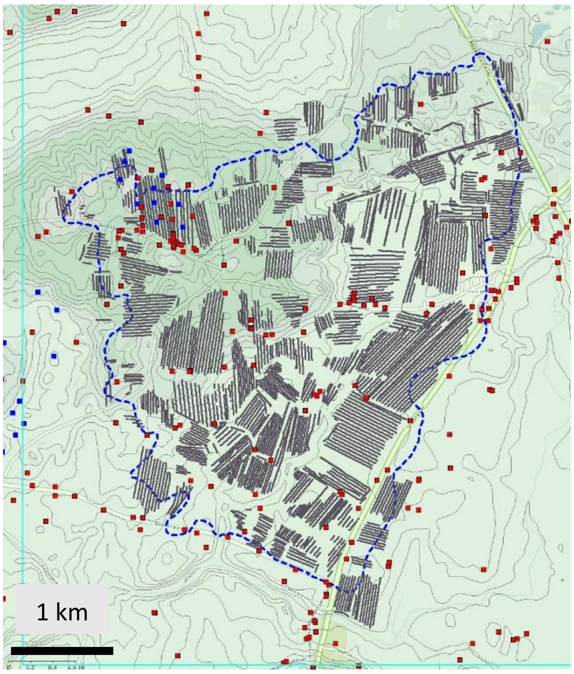


Figure 4: Ice-marginal positions: A) The Kattegat advance, B) The Main advance and C) Re-advance during the general recession of the Main advance. The study area is marked with yellow star. Maps from Larsen et al. (2009).

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 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 4A), the 'Main ice advance' from northeast (23-21.000 years ago; Figure 4B), and finally an easterly re-advance (19.000 years ago; Figure 4C). These ice advances will most likely be 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 formed between the ice-marginal hills. The patches of tills on the outwash plain (e.g. DGU no. 40. 1753) could be indicating that the following re-advance reached out over parts of the plain before finally melting away.

2 Geophysical data and boreholes



Four types of geophysical data have been collected in and just around the study area (Figure 5):

- TEM data (Transient Electro Magnetic method; blue spots on Figure 5)
- tow-TEM data (tTEM; grey lines on Figure 5)
- Schlumberger soundings (a limited number in NW part; not shown on Figure 5)
- Paces lines (Pulled Array Continuous Electrical Soundings; a limited number in NW part; not shown on Figure 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).

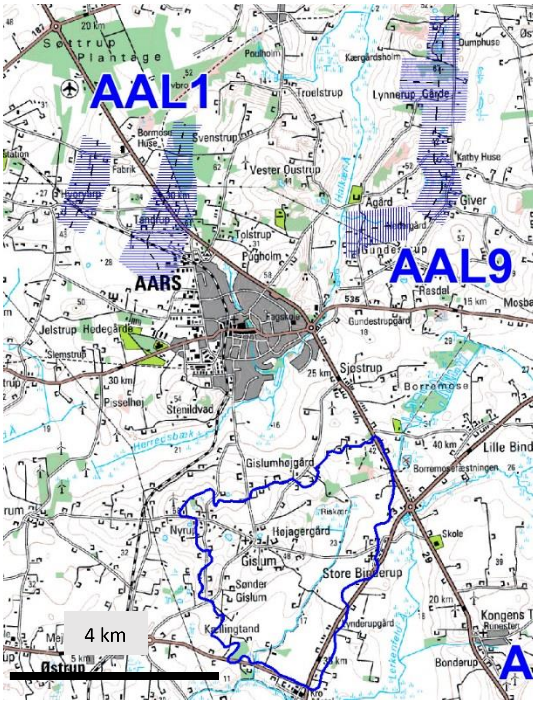
*Figure 5: Geophysical data and boreholes. TEM data is from the Gerda database and borehole data from the Jupiter database (*www.geus.dk*).*

3 Stratigraphy from borehole data

Based on borehole data within the study area, the oldest parts of the sedimentary succession consist of light olive grey sticky marine clay from the Eocene (e.g. DGU no. 40.1006). Above, layers of dark greenish-grey, glauconitic mica clay of presumably Oligocene age have been found (e.g. 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 is fairly varied – 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 a few meters thickness can be found in boreholes in the lowest parts of the terrain. Isolated floes of pre-Quaternary sediments occur within the Quaternary succession pointing to glaciotectonic deformation (e.g. 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 (DGU no. 40.1022).

4 Buried tunnel valleys



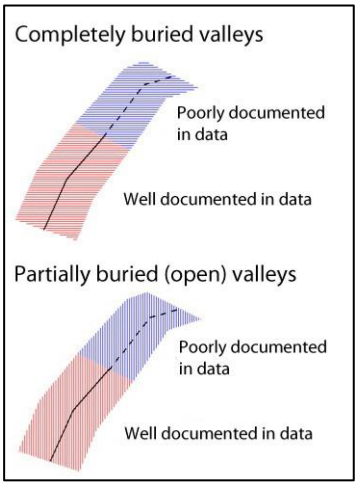


Figure 6:
Mapped buried valleys north of the study area. Legend for the map is shown above; "AAL1" refers to locality numbers used in Sandersen & Jørgensen (2016) and on www.buried-valleys.dk.

Figure 6 shows the buried valleys that have been mapped just north of the study area. The buried valleys were generally formed as tunnel valleys by meltwater underneath the ice sheets. 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 1 and 6). The mapped valleys may represent several generations, but the two orientations match fairly well the orientations of the youngest ice-advances mentioned earlier.

5 Geological interpretation of geophysical data

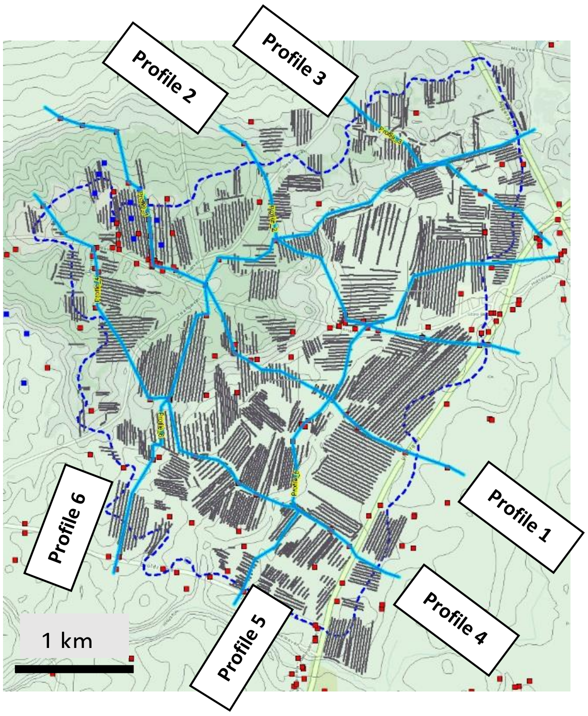


Figure 7: Location of selected profiles.

The very good tTEM data coverage and the nearly seven boreholes per square kilometre gives a very 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 (Figures 12 to 17) are shown on Figure 7 and Figures 8 to 11 show four 2½ m slices of tTEM mean resistivities. A grey hatched line marks the boundary between the glacial hill and the outwash plain (see Figure 2).

The deepest slice (Figure 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 west, high resistivities are also seen (Figures 8 and 9), but the appearance is rather patchy and the boundary to the low-resistivities is irregular.

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

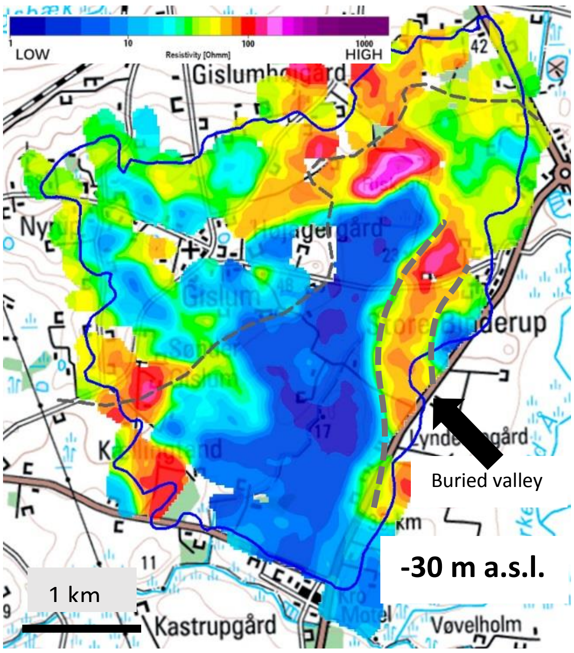


Figure 8: Mean resistivity of tTEM data; slice -30 m a.s.l.

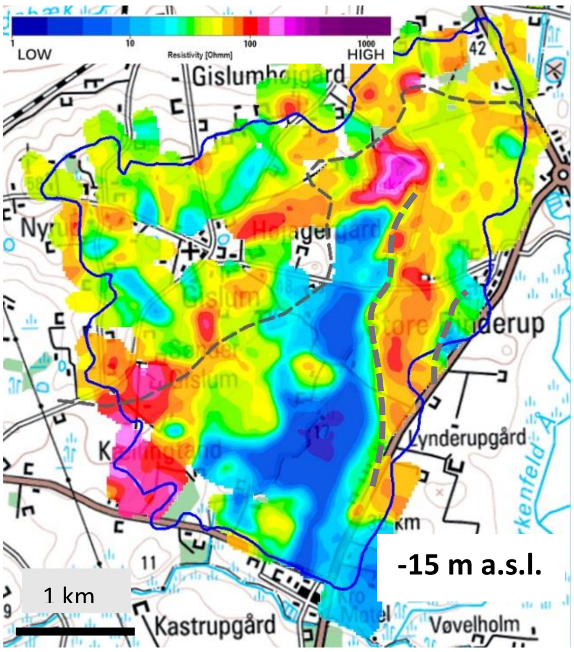


Figure 9: Mean resistivity of tTEM data; slice -15 m a.s.l.

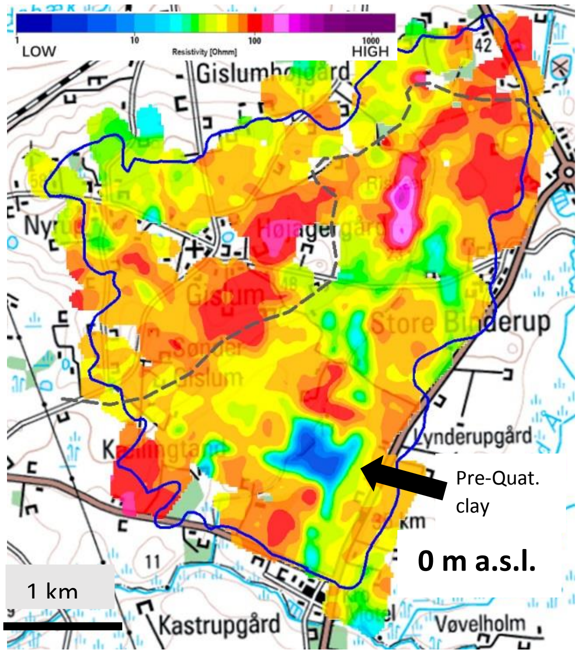


Figure 10: Mean resistivity of tTEM data; slice 0 m a.s.l.

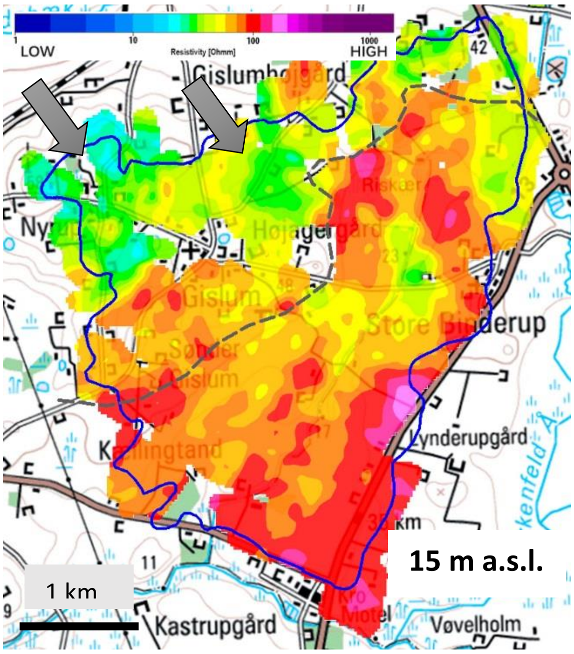


Figure 11: Mean resistivity of tTEM data; slice +15 m a.s.l.

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 10). At higher elevations, there is a gradual increase in the level of resistivity, showing an increasing dominance of sand and gravel. However, as seen on Figure 11, layers of moderate to low resistivities are present to the north and northwest (green to bluish colours; grey arrows on Figure 11). 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 fairly 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 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 1022).The sample descriptions show glacial sediments with high content of pre-Quaternary material from 0 m a.s.l. and down.

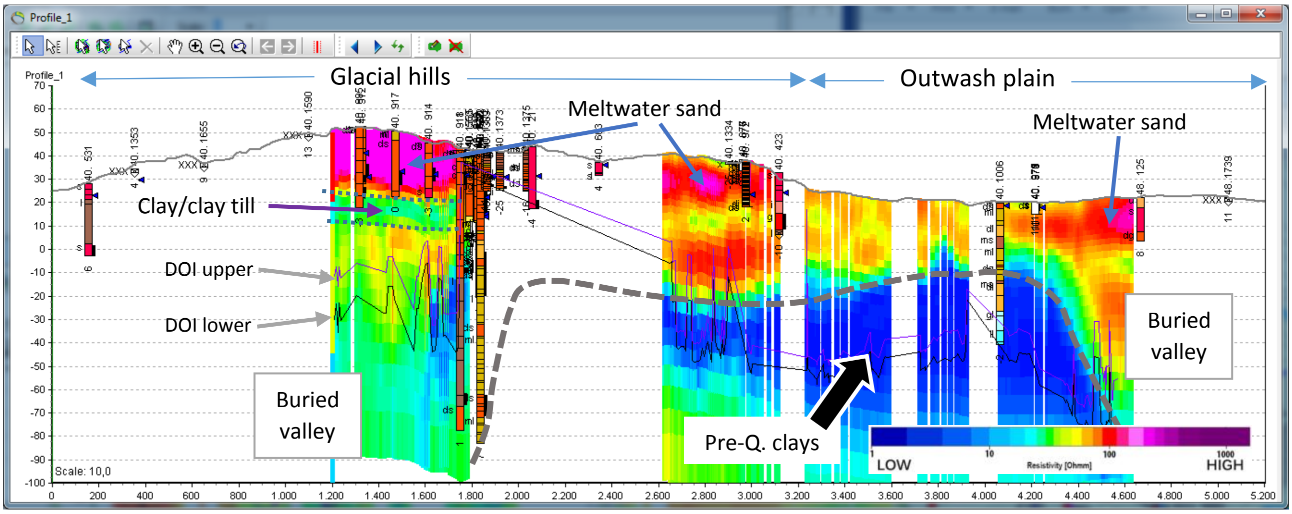


Figure 12: Profile 1; NW-SE. For location, see Figure 7. Depths of investigation (DOI) are shown with thin purple and black lines. (All profiles have the same vertical exaggeration, but they differ in length).

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, but dominated by clay. To the south-west, the flank of the narrow buried valley marked with an arrow on Figure 8 is seen. The valley in-fill is high-resistive end 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 11 (grey arrows). On Profile 1, this clay layer apparently disappears or thins out underneath the outwash plain to the southeast.

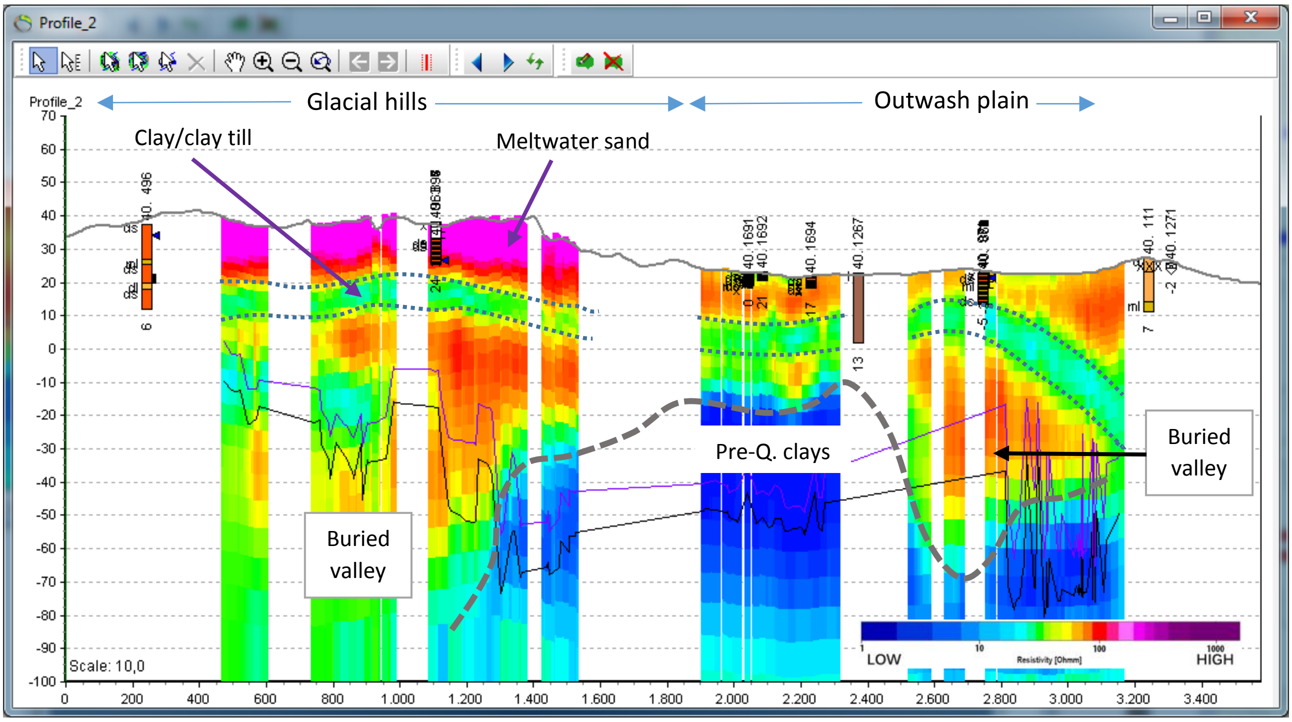
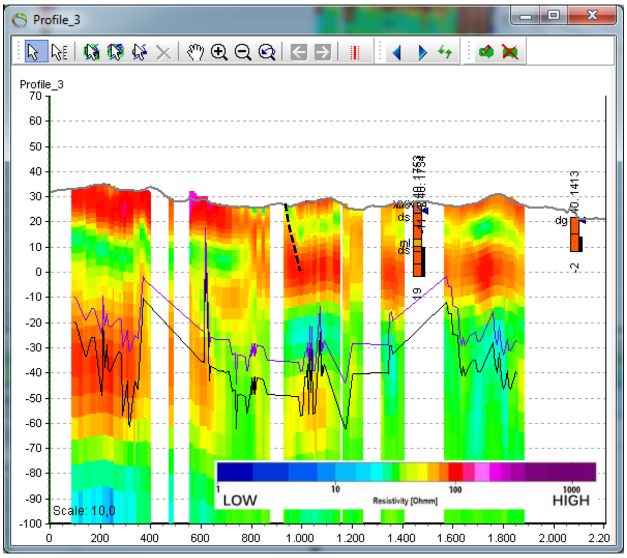


Figure 13: Profile 2; NW-SE. For location, see Figure 7. (All profiles have the same vertical exaggeration, but they differ in length).

Profile 2 in Figure 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 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 seems to be located very deep and way below the DOI.

Figure 14: Profile 3; NW-SE. For location, see Figure 7. (All profiles have the same vertical exaggeration, but they differ in length).

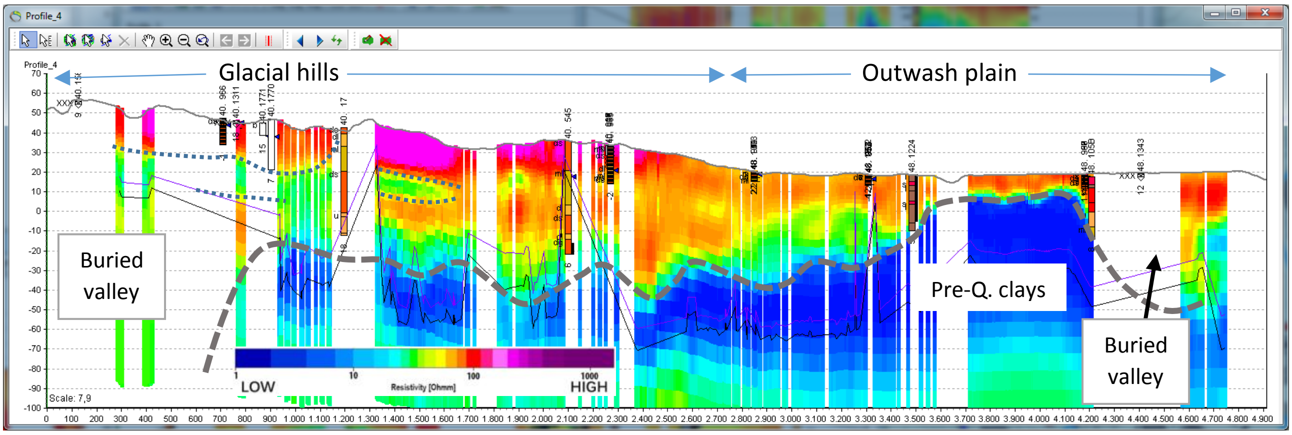


Figure 15: Profile 4; NW-SE. For location, see Figure 7. (All profiles have the same vertical exaggeration, but they differ in length).

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 has a small plateau to the southwest (between 3500 and 4200 m) – the same which is seen in the lower central part of figure 10. Just to the right of this on the profile, is the narrow buried valley. Between the buried valley to the northwest and the clay plateau to the southeast, there is a "basin" eroded into the pre-Quaternary clay (seen as moderate to high resistivities southwest on Figure 9). Apparently, the clay layer in the upper part of the Quaternary succession is not present underneath the outwash plain.

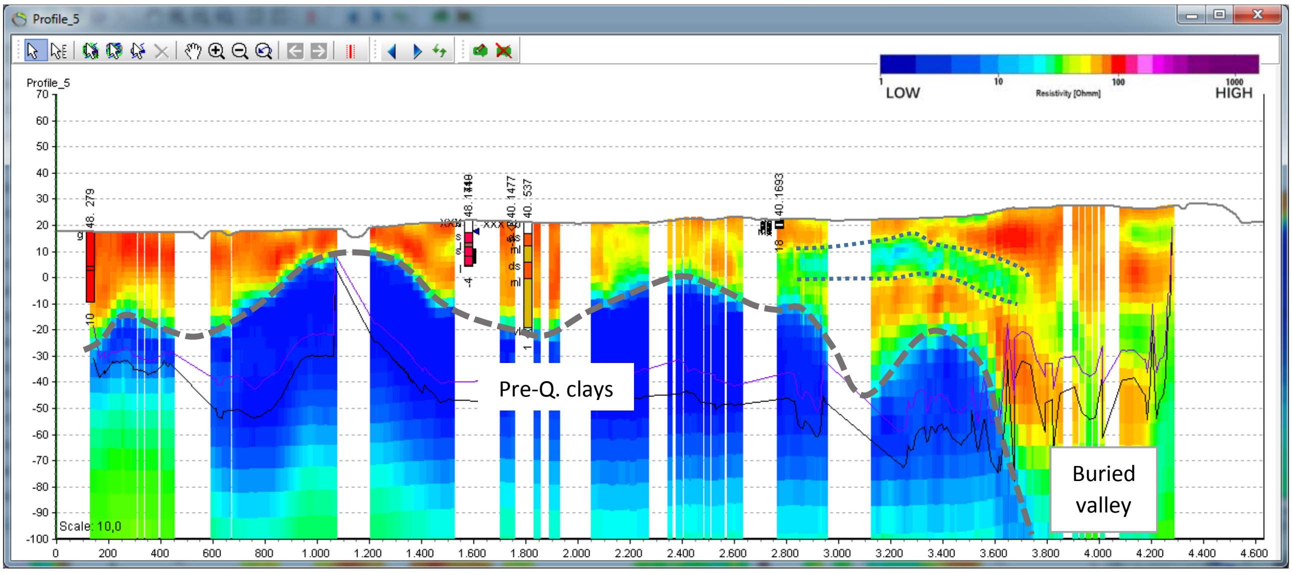


Figure 16: Profile 5; SW-NE. For location, see Figure 7. (All profiles have the same vertical exaggeration, but they differ in length).

On Profile 5 (Figure 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 17 crosses the glacial hills from southwest and to northeast across the outwash plain and the low hills just north of the plain. Above the pre-Quaternary sediments, the Quaternary sequence is clearly dominated by high-resistive sediments, and underneath the glacial hills, the clay is situated at the level that we would expect. 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.

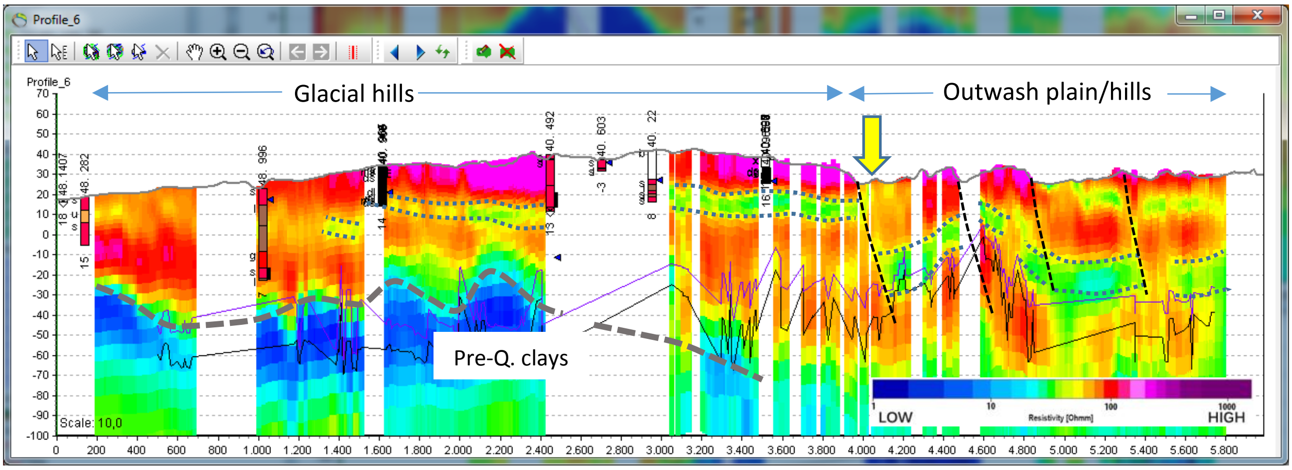


Figure 17: Profile 6; SW-NE. For location, see Figure 7. (All profiles have the same vertical exaggeration, but they differ in length). Yellow arrow points to areas of the outwash plain with occurrence of peat in upper layers.

A similar observation could be made on Profile 3 (Figure 14). Inferred faults have been sketched on figure 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 has been described from other outwash plains in Denmark (Lykke-Andersen et al., 1996; Sandersen & Jørgensen, 2015). Extensive occurrences of peat are found on the part of the outwash plain bordering the hills where the inferred offset is largest (yellow arrow on Figure 17).

6 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 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 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 northeast or east as could be expected have not been recognized with certainty within the study area. The topography of the surrounding areas, show 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 floes 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. The occurrences of surficial patches of tills on the outwash plain could mean that the youngest advance from the east could have overridden parts of the study area.
- **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 points to deformations 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. If these preliminary

observations are confirmed by further investigations, this type of deformation of the sedimentary succession should be added to the possible glaciotectonic deformations when assessing the groundwater vulnerability of the area.

- **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 cannot be found above 0 m a.s.l.
- **Geological interpretation and correlation:** The preliminary 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 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.

7 References

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