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1 Geomorphology

The Lillebæk study area is located in a glacial moraine landscape in the south-eastern part of Funen (Figure 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 as shown in Figure 1. To the east, the loop area is located in a glacial moraine landscape that extends towards the coast.

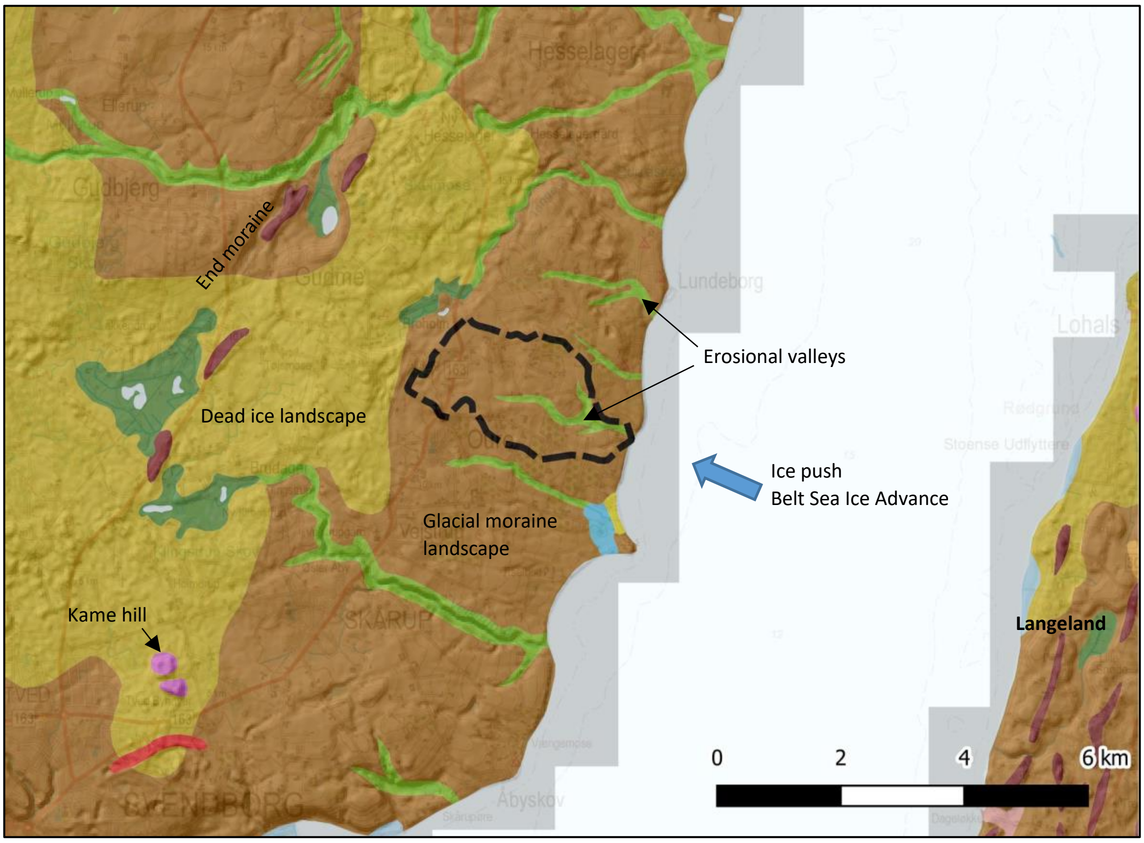

Figure 1: Morphological map. The Loop 4 study area marked with dashed black polygon and is located on a clay moraine landscape from the last glaciation (Weichselian) (GEUS, 2018).

The topography in the Loop 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 30-20 m a.s.l., while the erosional cliffs at the coastline in east show elevations around 10 m a.s.l. (Figure 2). Within the loop area, one large erosional valley is incised into the terrain surface, which also includes Lillebæk (Figure 2).

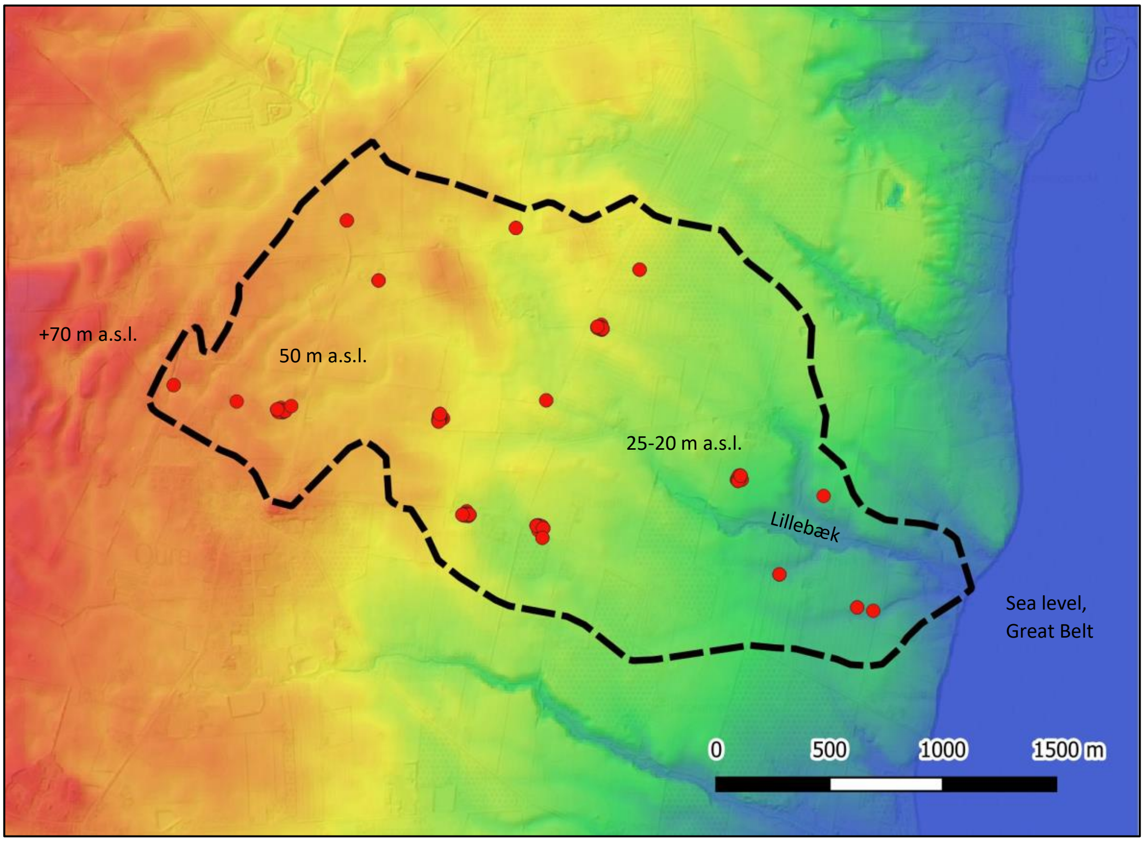

Figure 2. Digital elevation model (highest elevations: red, lowest: blue). Red dots represent Loop stations.

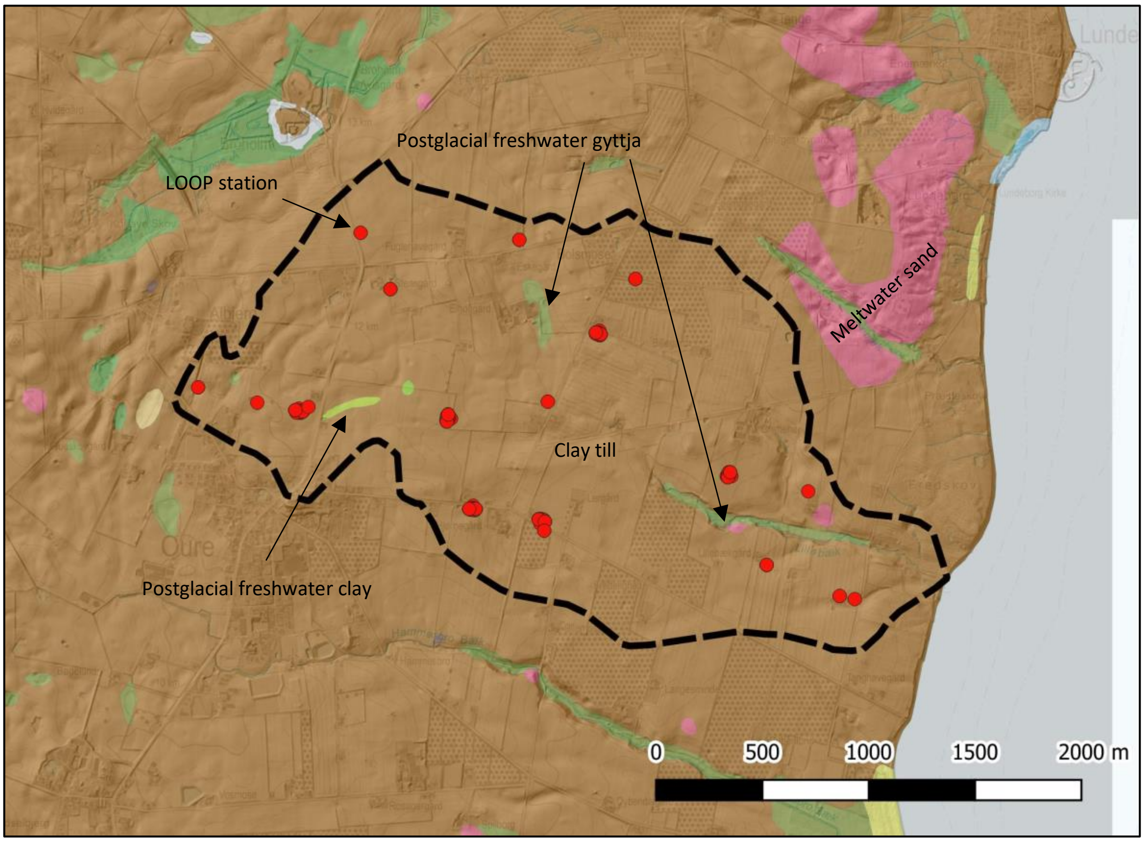

Figure 3. Soil types in the uppermost meter (Jakobsen et al. 2011). Brown colours: Tills; Red: Meltwater sand; Green: Postglacial freshwater deposits (gyttja and clay). Red dots represent LOOP stations.

A map of the soil types in the uppermost meter is shown on Figure 3. Glacial tills are the dominating the study area. North of the study area occurrences of meltwater sands are found, which in boreholes are described as the “White Sand”. This local unit is almost pure quartz sand – presumably not meltwater sand, but more likely deposited by wind in an expected ice-free period during the Weichselian (Friis & Larsen 1975; Larsen 2002); see later description. Postglacial freshwater deposits are found locally in topographic lows and the area of Lillebæk (Figure 3).

The extent of the Late Weichselian Belt Sea advance is visualised on Figure 4. The Lillebæk Loop area is shown with a red circle and is located rather close to the margin of the Belt Sea advance.

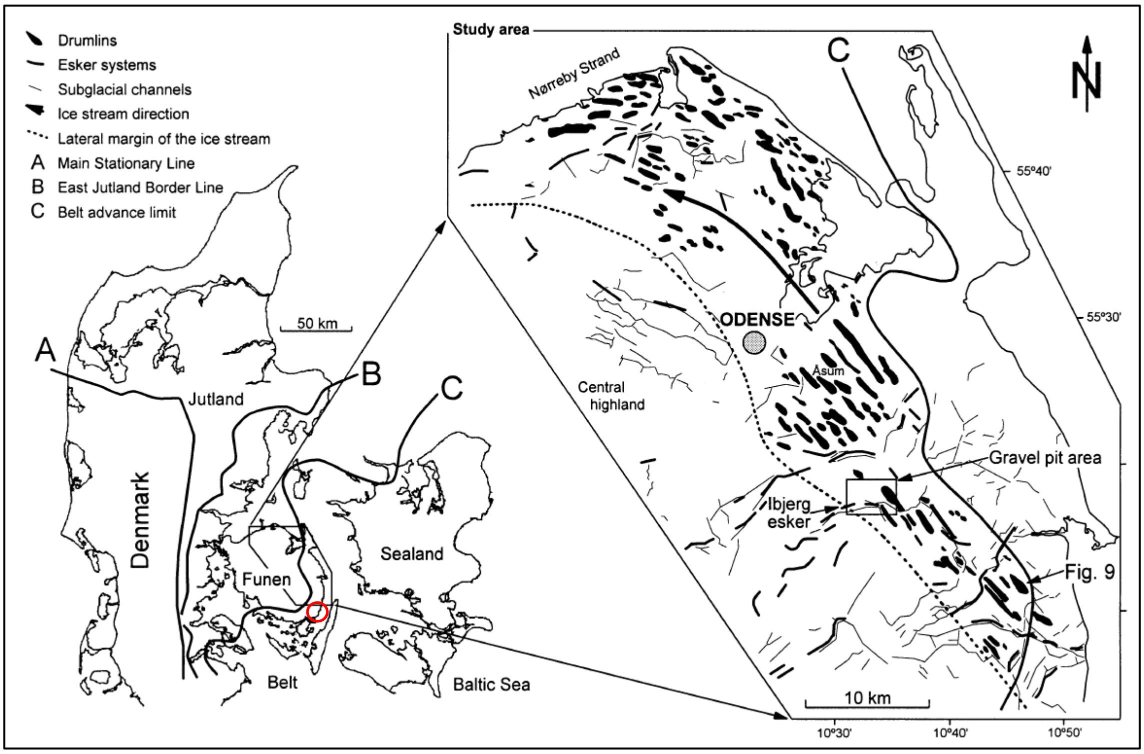

Figure 4. Overview on ice advances and (Jørgensen and Piotrowski, 2003)

2 Geophysical data and boreholes

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

a. Tow-TEM data (tTEM) shown as small black points
b. SkyTEM data (airborne Transient Electro Magnetic method) shown as red points
c. TEM40 data (ground-based Transient Electro Magnetic soundings) shown as red squares
d. PACES data (Pulled Array Continuous Electrical Sounding) shown as purple triangles/lines
e. The geological data comprise boreholes from the Jupiter database (black dots).

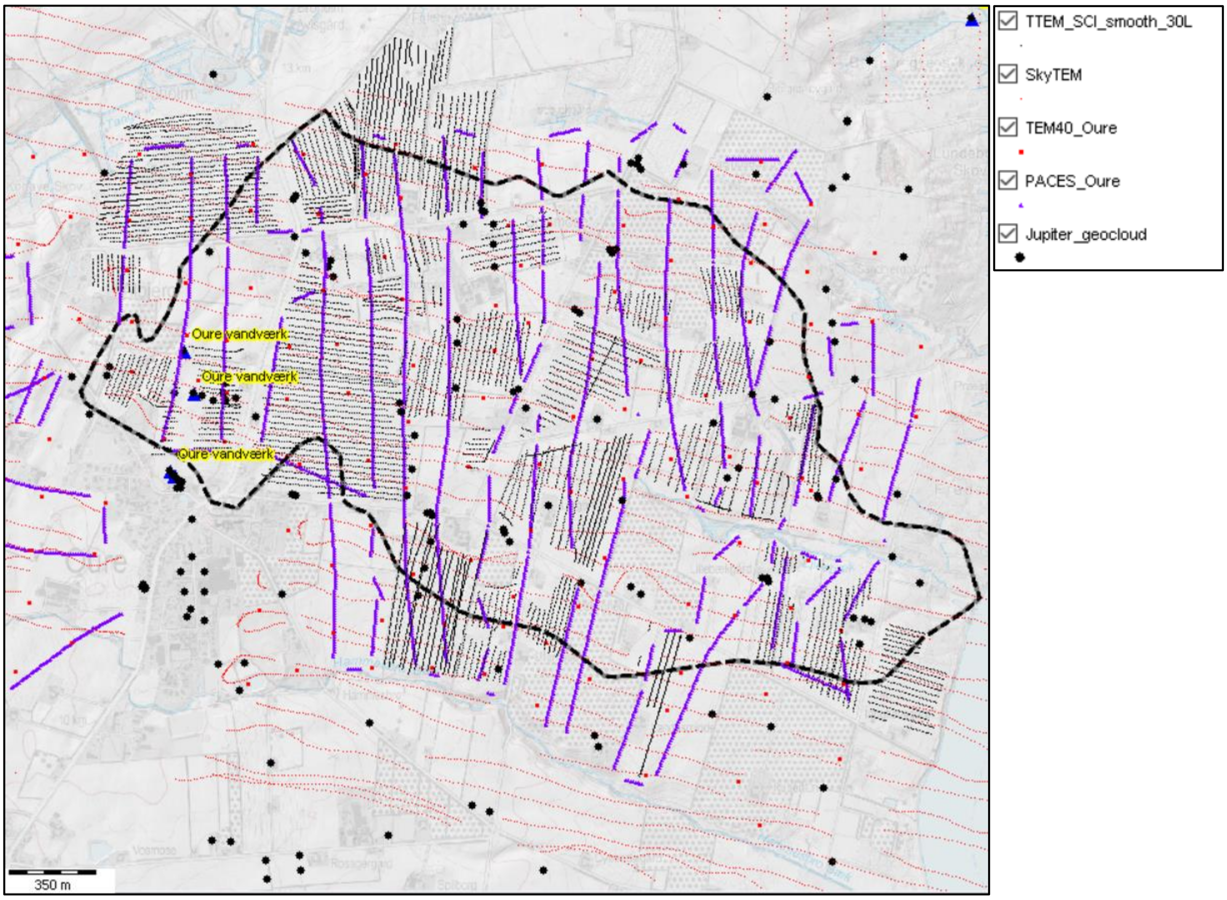

Figure 5. Boreholes (Jupiter and GRUMO) and geophysical datasets in the area. Legend is shown to the right.

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

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 at Figure 5.

3 Stratigraphy

Pre-Quaternary

The island of Funen is located on the NW-SE trending Ringkøbing-Fyn High (red lines on Figure 6). On this structure, NW-SE and N-S orientated faults have been mapped below Funen. The elevation of the pre-Quaternary surface is closely related to the presence of this structural high, see Figure 6, and the surface of the pre-Quaternary forms a NW-SE orientated subsurface hill underneath Fyn.

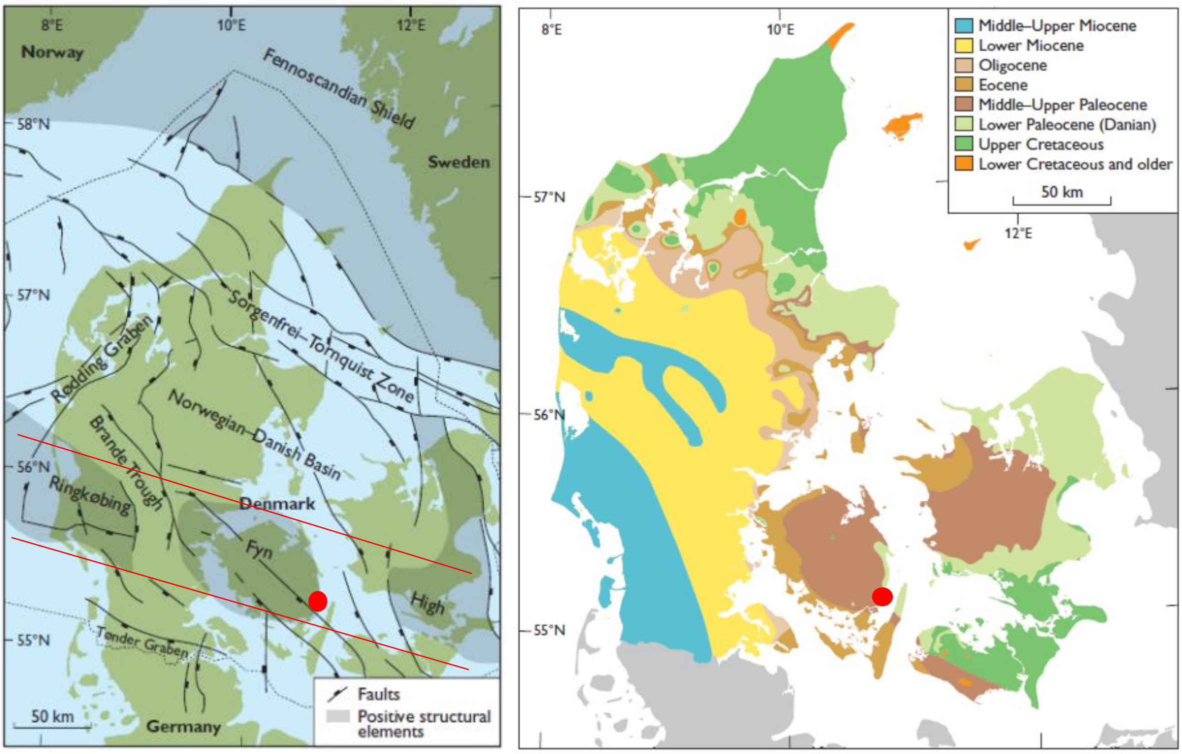

Figure 6. Left: Deep-seated tectonic structures – Ringkøbing-Fyn High. Right: Pre-Quaternary surface of Denmark. Lillebæk Loop area is shown with red dot (both from Rasmussen et al. 2010).

The uppermost pre-Quaternary deposits consist of Paleocene clay of varying thicknesses with Danian limestone and Cretaceous chalk below. The Danien 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, 2016); see Figure 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.

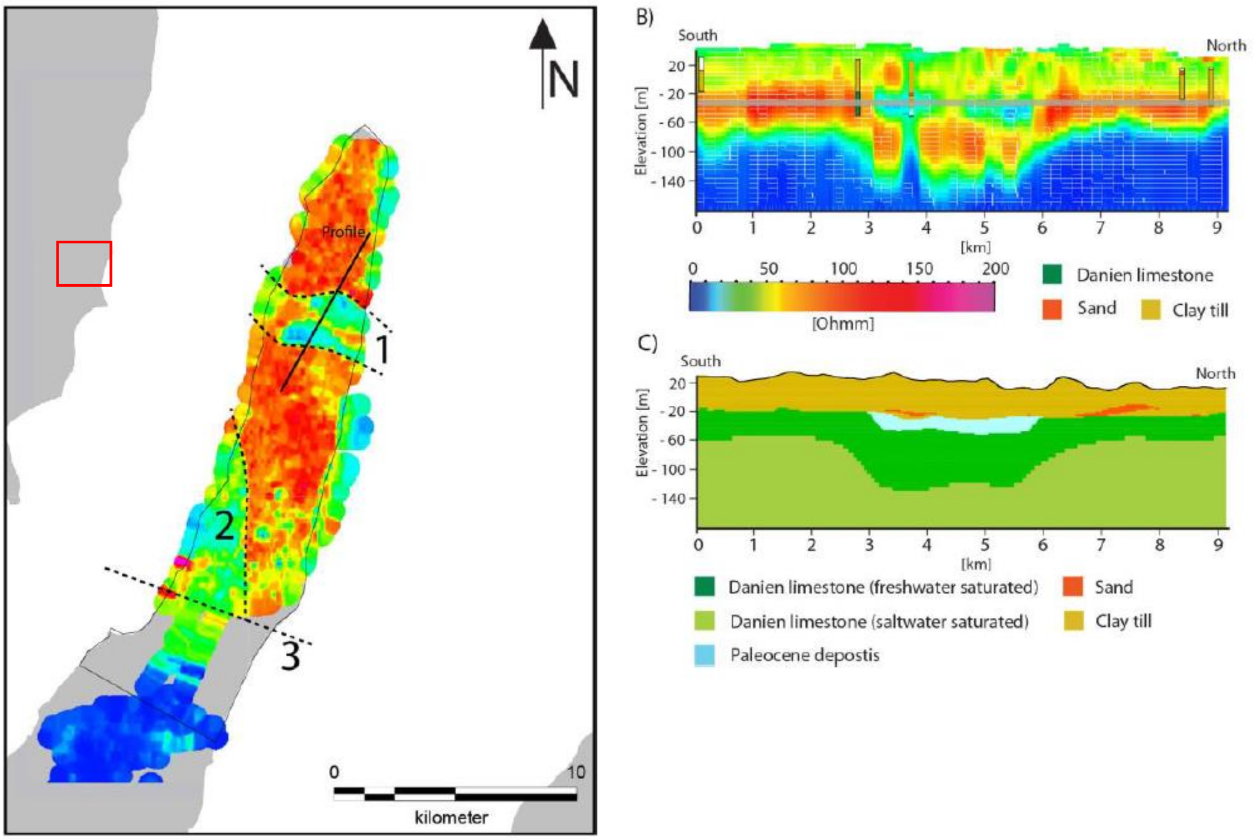

Figure 7. SkyTEM survey at Langeland (from Andersen 2016). Left: Resistivity grid at elevation -25 m. '1' indicates area of down faulted limestone and chalk. The loop area is marked with a red square 5 km to the west. Right: B) SkyTEM resistivity profile and C) Geological interpretation.

A geological interpretation of the geological setting has been made in the process of mapping buried valleys in the area; see Figure 8 (Sandersen and Jørgensen, 2016). The interpretation fits well into the geological understanding of the deeper succession described further in section 5 – "Geological interpretation of geophysical data".

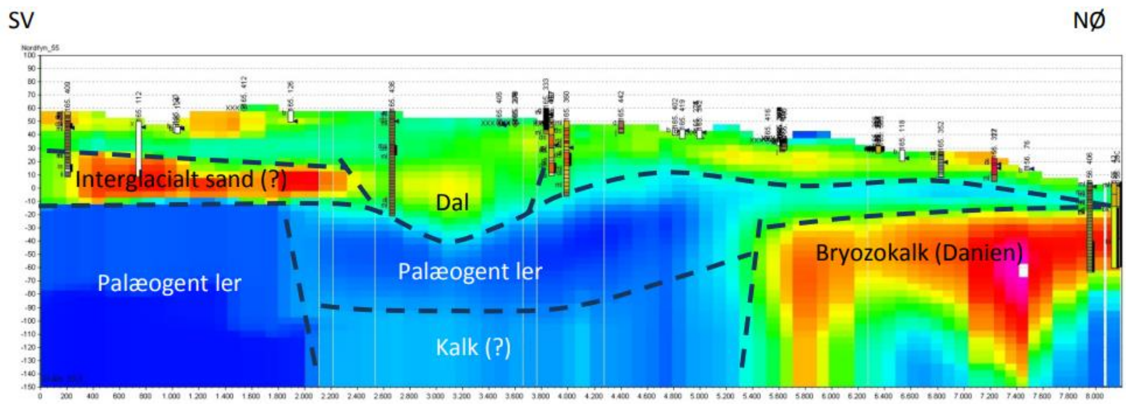

Figure 8. From. Geological interpretation of the buried valley ODE11 (from www.buried-valleys.dk).

Quaternary

The Quaternary succession consists of clayey tills, meltwater sand, meltwater clay and quartz sand proposed to be deposited by wind in an ice free period during the Weichselian (Friis & Larsen, 1975; Larsen, 2002). The thickness of the Quaternary succession vary in thickness from approx. 15 m and to more than 60 m. Many ice advances has covered the Loop area resulting in a complex quaternary stratigraphy. Old glacial deposits from before The Weichselian has predominantly been eroded away while deposits from the latest ice advances dominate the quaternary succession (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). In some boreholes, the sand is interpreted as interglacial and the sand is generally calcium free (GEUS Jupiter-database).

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 soil map (Figure 3) (keeping in mind that the sand described as meltwater sand in the soil map is believed to be quartz sand). However, the very varying Quaternary sediments at depth makes the interpretation of tTEM resistivities challenging.

4 Buried tunnel valleys

Figure 9 below, shows the 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).

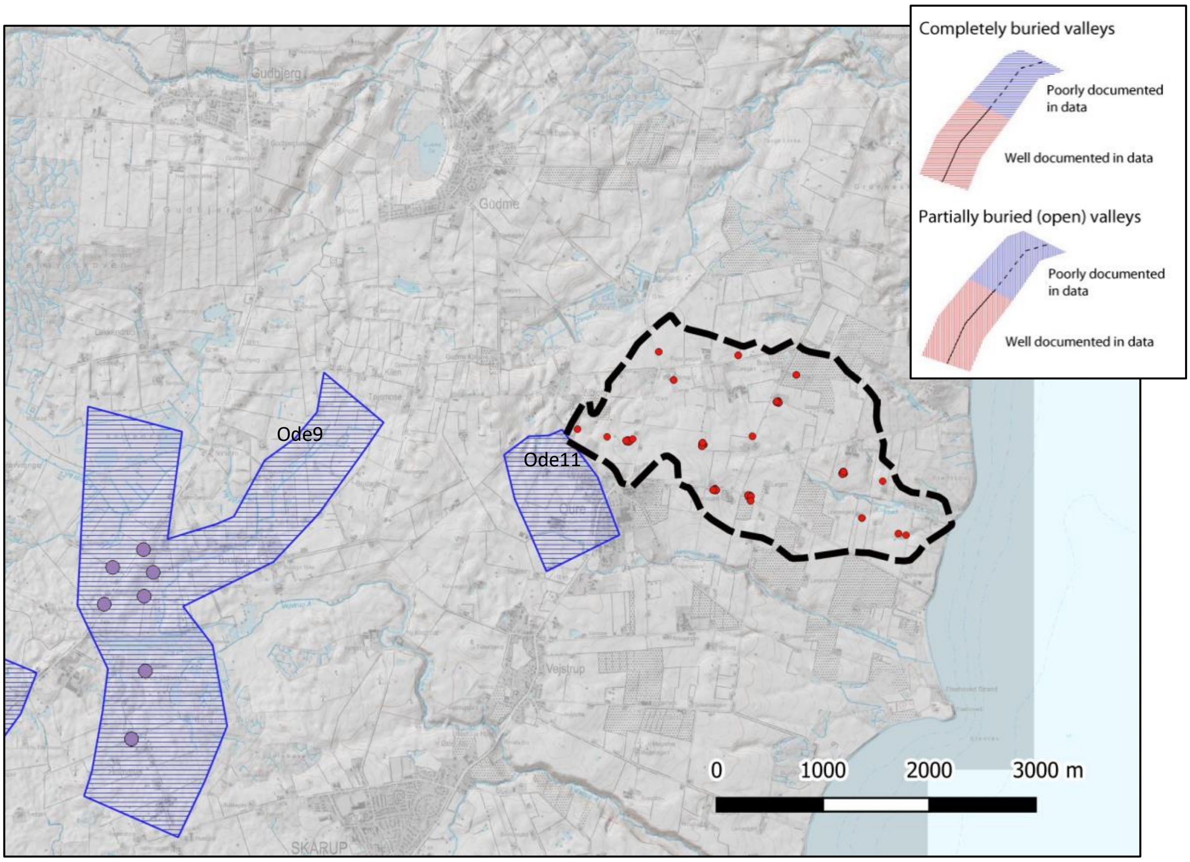

Figure 9. Mapped buried valleys close to the study area (shown with black hatched line). Legend for the map is shown above (Sandersen & Jørgensen, 2016) and on www.buried-valleys.dk)

5 Geological interpretation of geophysical data

The Lillebæk Loop area has a full SkyTEM coverage (Figure 5) 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 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 x2 m discretization.

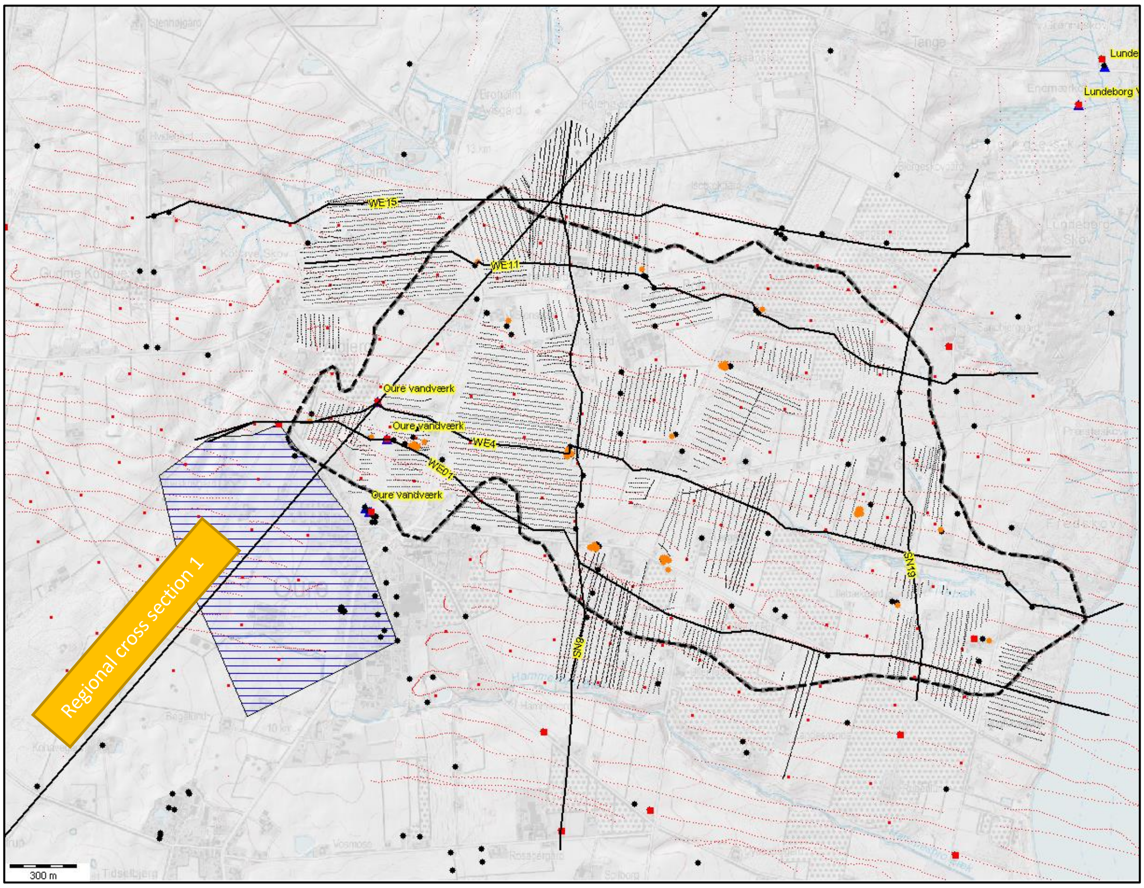

Figure 10. Cross-section overview. Cross sections: Black lines (the), tTEM: red dots, SkyTEM: purple dots, MEP (ERT): green lines, Boreholes: black dots.

In the following, preliminary interpretations have been performed on the cross-sections shown in Figure 10 and on selected 2D resistivity maps (Figure 11).

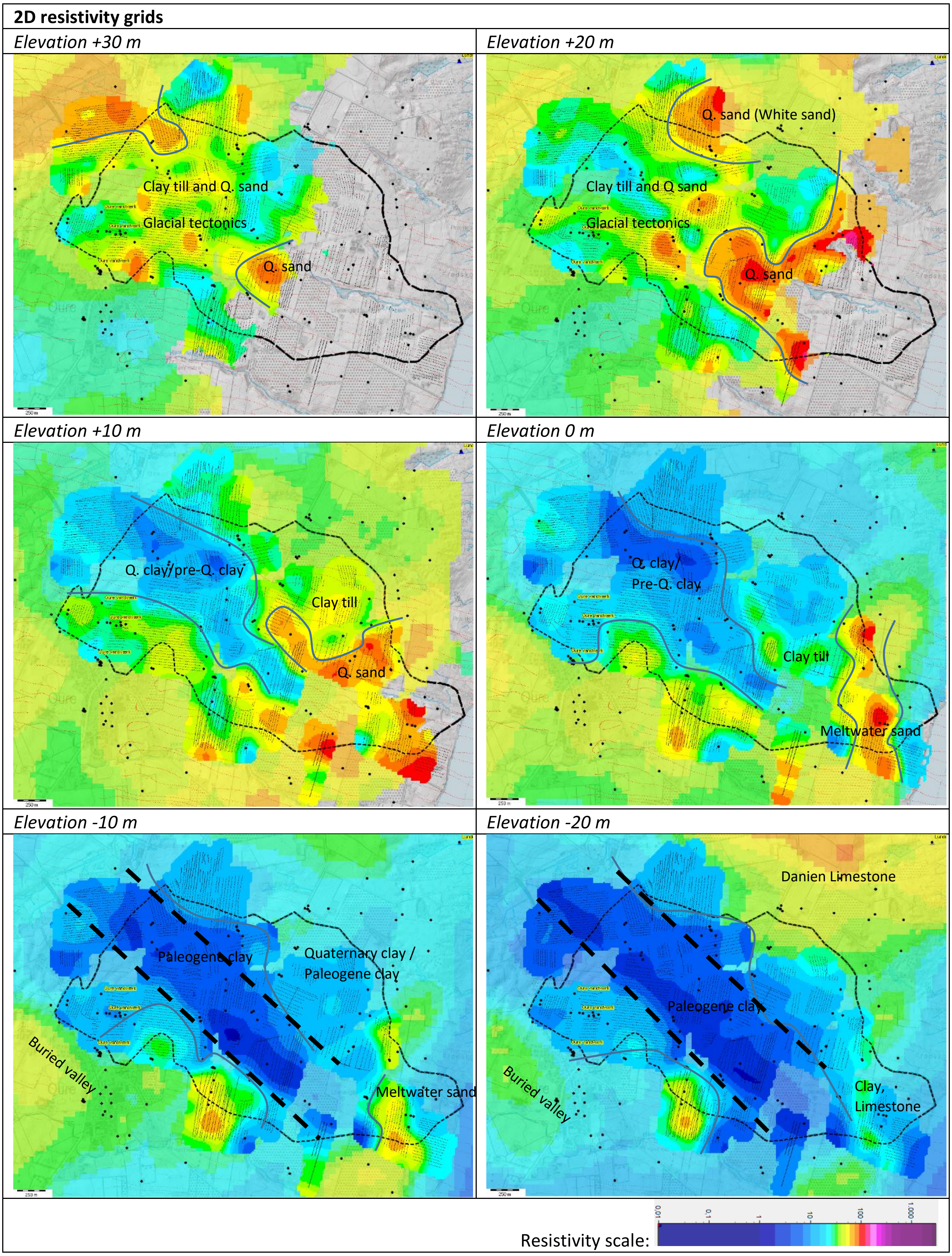

Figure 11. 2D resistivity grids of the tTEM dataset (tTEM smooth models, 30 layers, 100 % opacity). Background are combined 2D resistivity slices for TEM40 and SkyTEM (opacity 60 %). Black dots represent Jupiter boreholes.

Figure 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 m, +20 m, +10 m, 0 m, -10 m and -20 m, 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 (expected Quartz sand/White sand and meltwater sand) shows moderate to high resistivities, whereas the clay till and meltwater clay shows low to moderate resistivities (blue-greenish colours). Parts of the upper clay till shows low resistivities, which is expected to be due to reworked Paleogene clays in the till.

At the the deep levels (approx. 0 m 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, 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 12 below, is a 10 km long regional profile orientated SW-NE. It crosses the loop area from 5500 m – 7500 m and gives a first overview of the deeper geology. As mentioned in e.g. Sandersen & Jørgensen 2016, it is proposed that fault activities in the pre-Quaternary 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 m) compared to the northeast. Palaeogene clays are thin or absent northeast of the fault. SkyTEM restivities indicate saline groundwater in the Danian limestone below -70 to -60 m 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 Palaeogene clay.

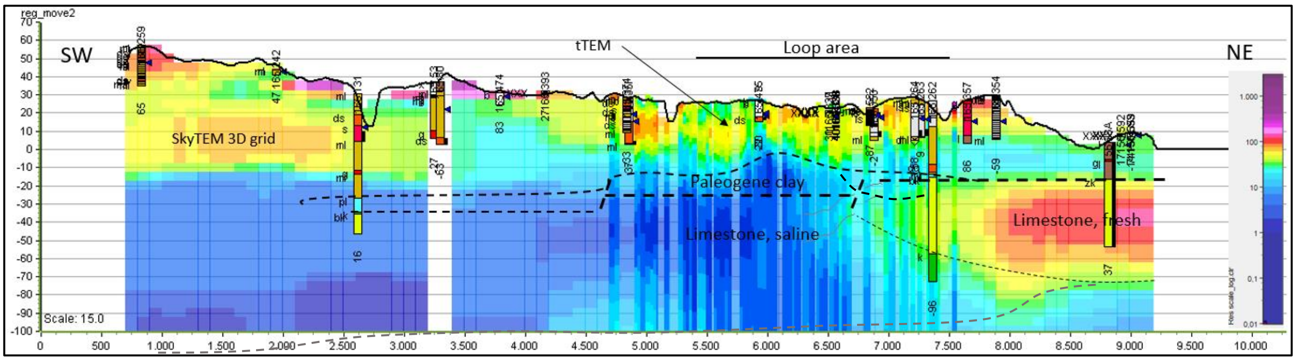

Figure 12. Regional cross section 1, SW-NE. For location, see Figure 10. TTEM data are shown as single sounding poles and SkyTEM data are visualized as 3D resistivity grid.

Cross section WE01 (Figure 13) gives a W-E overview of the southern part the study area, from the high elevations (+50 m) in the west towards the coastline in east. The transition to the Paleogene in the central part stands out quite clear in the geophysics - going from high resistivities (interpreted as meltwater sand/possible White Sand?) to resistivities below 10 Ohmm (blue colours). As sketched at the cross-section the western part of the Quaternary succession is the most difficult to interpret as it 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) at e.g. 3400 m.

A 10-20 meter thick sand layer from 2200-3600 m 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. 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 glacier erosion of the Paleogene clay that is expected to have been incorporated in the clay till. At 3600-4000 m on the cross section WE01, high resistivities indicate a buried valley with a N-S trending orientation apparently parallel with the coastline.

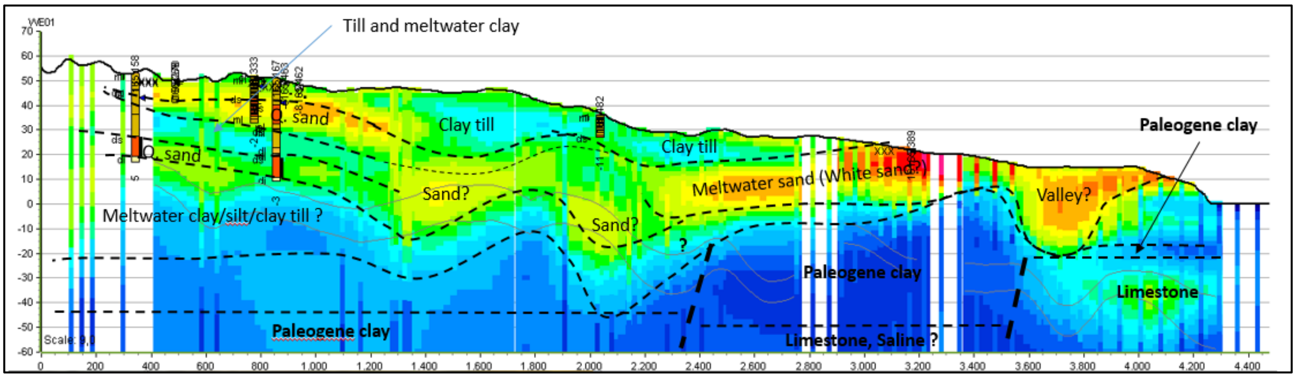

Figure 13. Cross-section WE01, W-E. For location, see Figure 10. TTEM data are shown as a 3D resistivity grid. SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section in Figure 14 (WE4) crosses the loop areas from west to east, see location at Figure 10. The cross-section shows the same picture as WE01: a) a highly glacially deformed Quaternary sequence above +30 m; b) a sand deposit (meltwater sand/White Sand) in the central part with a 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.

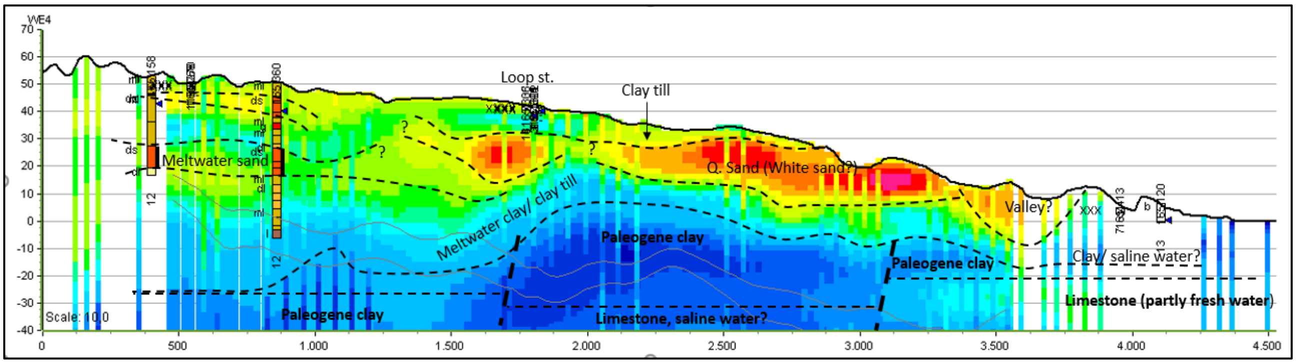

Figure 14. Cross section WE4, W-E. For location, see Figure 10. TTEM data are shown as 3D resistivity grid. SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross section WE11 in Figure 15 illustrates somewhat the same as the prior cross section, but it crosses the northern part of 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 estimated thicknesses of 10-20 m. At 3200 m (East), borehole DGU no. 165.263 describes quartz-rich sand with no calcium content, which is interpreted as "The White Sand", specified as interglacial sand in the Jupiter description. It likely that it 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 cross section) and east (2800 m – 3400 m). Below the resistive sand aquifer the resistivities are moderate to low, which combined with borehole information is interpreted as old clay till and meltwater clay deposit. 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.

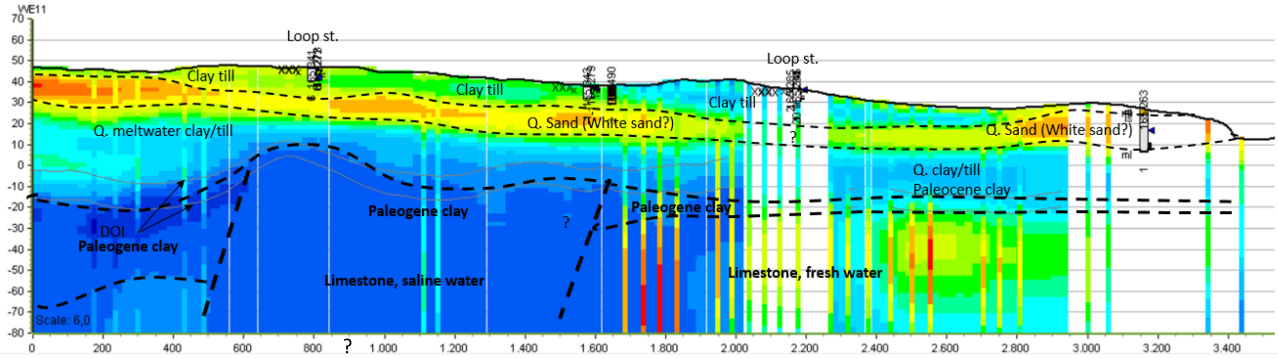

Figure 15. Cross section WE11, W-E. For location, see Figure 10. TTEM data are shown as 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross section WE15 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.

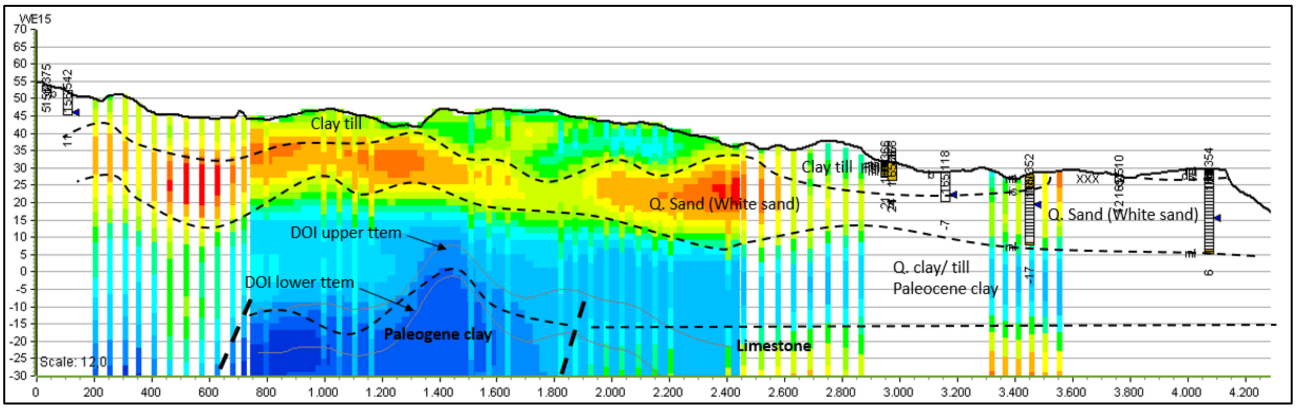

Figure 16. Cross section WE15, W-E. For location, see Figure 10. TTEM data are shown as 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section SN09 below (Figure 17**Fejl! Henvisningskilde ikke fundet.**) 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 geophysics show moderate resistivities down to -30 to -35 m, which could indicate a buried valley (maybe connected to the same system as the buried valley shown on figure XX). 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 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 likely deformed.

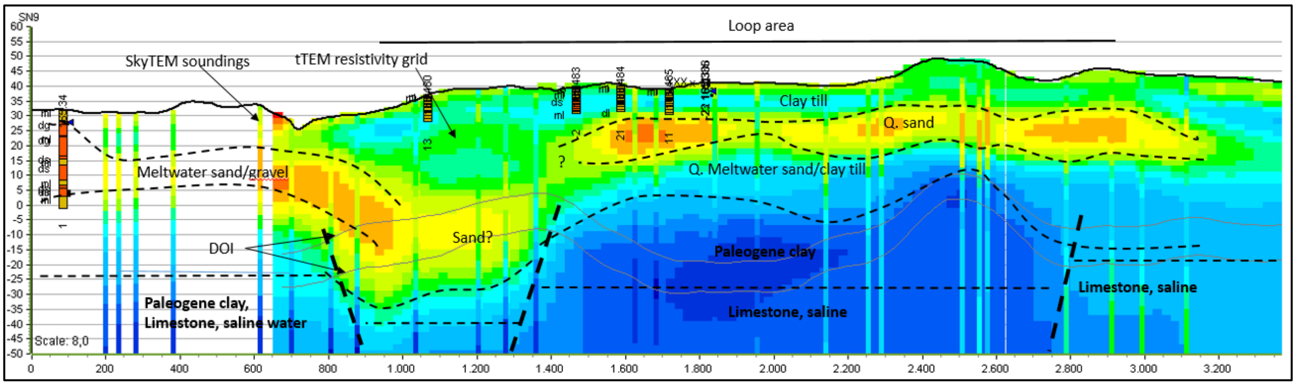

Figure 17. Cross-section SN9, S-N. For location, see Figure 10. TTEM data are shown as 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

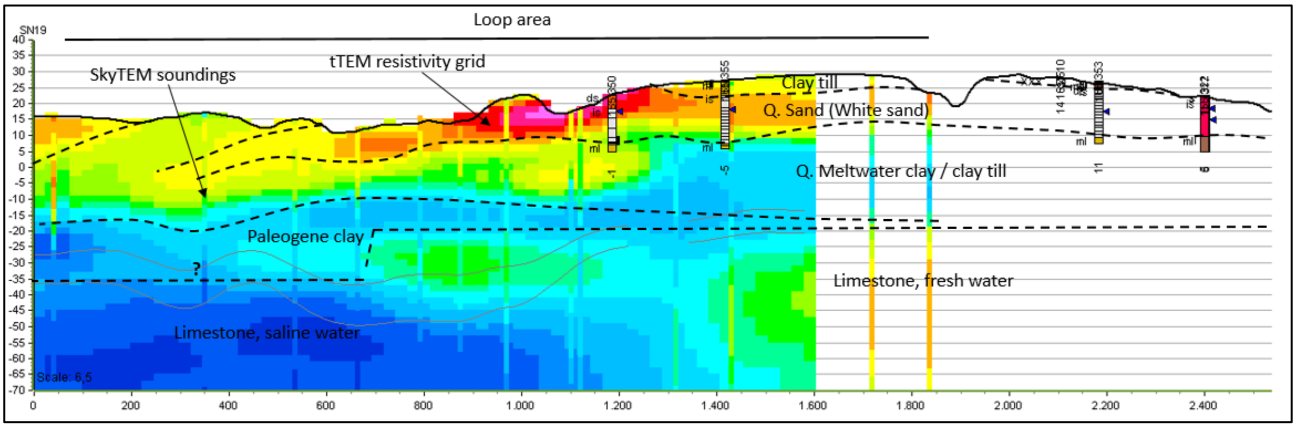

Figure 18. Cross section SN19, S-N. For location, see Figure 10. TTEM data are shown as 3D resistivity grid and SkyTEM data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross section SN19 (Figure 18) strikes S-N through the eastern part of the study area and illustrates the change in geological elements going from the lower parts in south with moderate resistivities, crossing Lillebæk 650 m, to the area with sands close to the surface described as interglacial sand (White Sand). Beneath the sand deposits, all boreholes describe clay till.

To summarize, the following different geological elements could be identified in this preliminary 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'. A local quartz sand unit possibly deposited by wind and can be distinguished by "normal" meltwater sand in color, it is calcium free, and the grains are well rounded. To the south and southwest, it becomes more difficult to follow this sand unit. This unit goes reaches the terrain level in some areas.
c. The southwestern part of the loop area at elevations above 30 m and towards the town of Oure, TEM data and boreholes indicate an area of large geological heterogeneity due glacial deformation.
d. In the eastern part, a possible S-N trending buried valley with mostly meltwater sand has been identified.
e. The pre-Quaternary succession is characterized the presence of Paleogene clays in the loop area due to downfaulting of the limestone/chalk deposits. To the north the top of the limestone is found at -15 m and contains fresh water, which is characterized by moderate to high resistivities in TEM. The outline of the pre-Quaternary surface is mainly interpreted using TEM because of lack of deeper boreholes.

6 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 are sparse as many of the boreholes are shallow, but the general perception of the upper succession is fairly good. The Quaternary sequence is only penetrated by a few boreholes and therefore the interpretations of the transition to 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 predominately defined as a glacial landscape of Late Weichselian age with occurrences of postglacial deposits in low-lying wet 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 this sand layers is present in the loop area. The glacial landscape in the southwestern part appears to be glacially deformed, whereas the eastern parts of the Quaternary sequence appears to be simpler. The deeper and older part of the Quaternary succession and the boundary to the Paleogene is difficult to distinguish precisely due to low 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 to elevations around 0 m. The Paleogene clays has likely been subject to repeated glacial erosion and deformation throughout the Quaternary.

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