Demo sites, Hulebro Bæk and Hagens Møllebæk, Salling Geological interpretations

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1 Geomorphology and surface geology

The Mapfield demo sites, Hulebro Bæk (demo site 1) and Hagensmølle Bæk (demo site 2) are located on the Salling Peninsula in the north-western part of Jutland in a clay-dominated moraine landscape from the last glaciation (The Weichselian Ice age), see Figure 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.

The topography in the demo site 1 is highest in northern north-western part with elevation up to 45 m a.s.l., while the highest topography in demo site 2 is western part with elevation up to 40-50 m a.s.l., see Figure 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). Hulebro Brook cuts through the terrain with a north-south/southeast 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 Brook. 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 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 creek within the catchment (demo site 2).

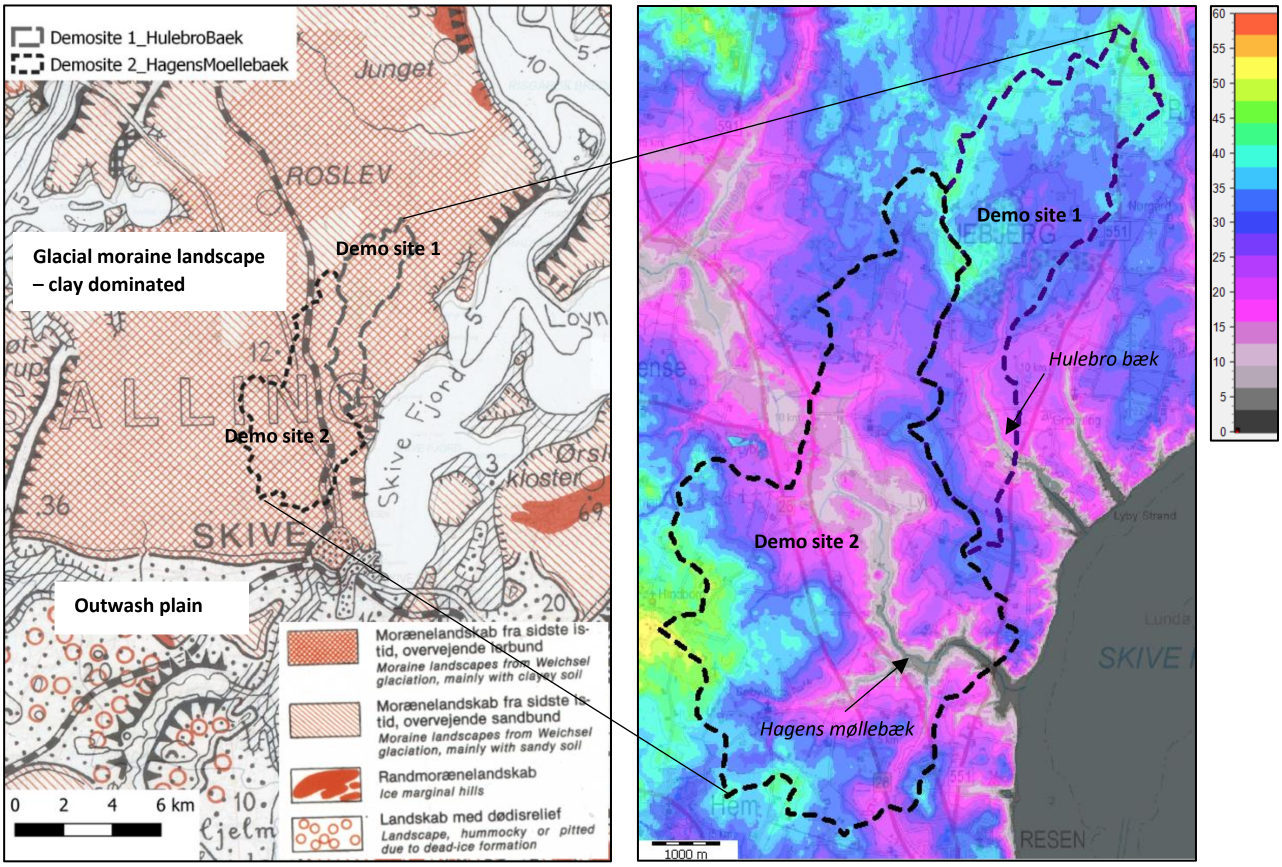


Figure 1: Left: Map for regional surface geomorphology of Demo site 1. The two demo sites are marked with dashed) polygons. They are both located on a clay-dominated moraine landscape from the last glaciation (Weichselian) (GEUS, 2018). Right: Digital elevation model (highest elevations: green, lowest: grey-black). Legend (m) in upper right corner.

Figure 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 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 the area of Hulebro Brook and Hagensmølle Brook. Meltwater sand deposits at the surface are mostly described around Lyby in the northern part of demo site 2.

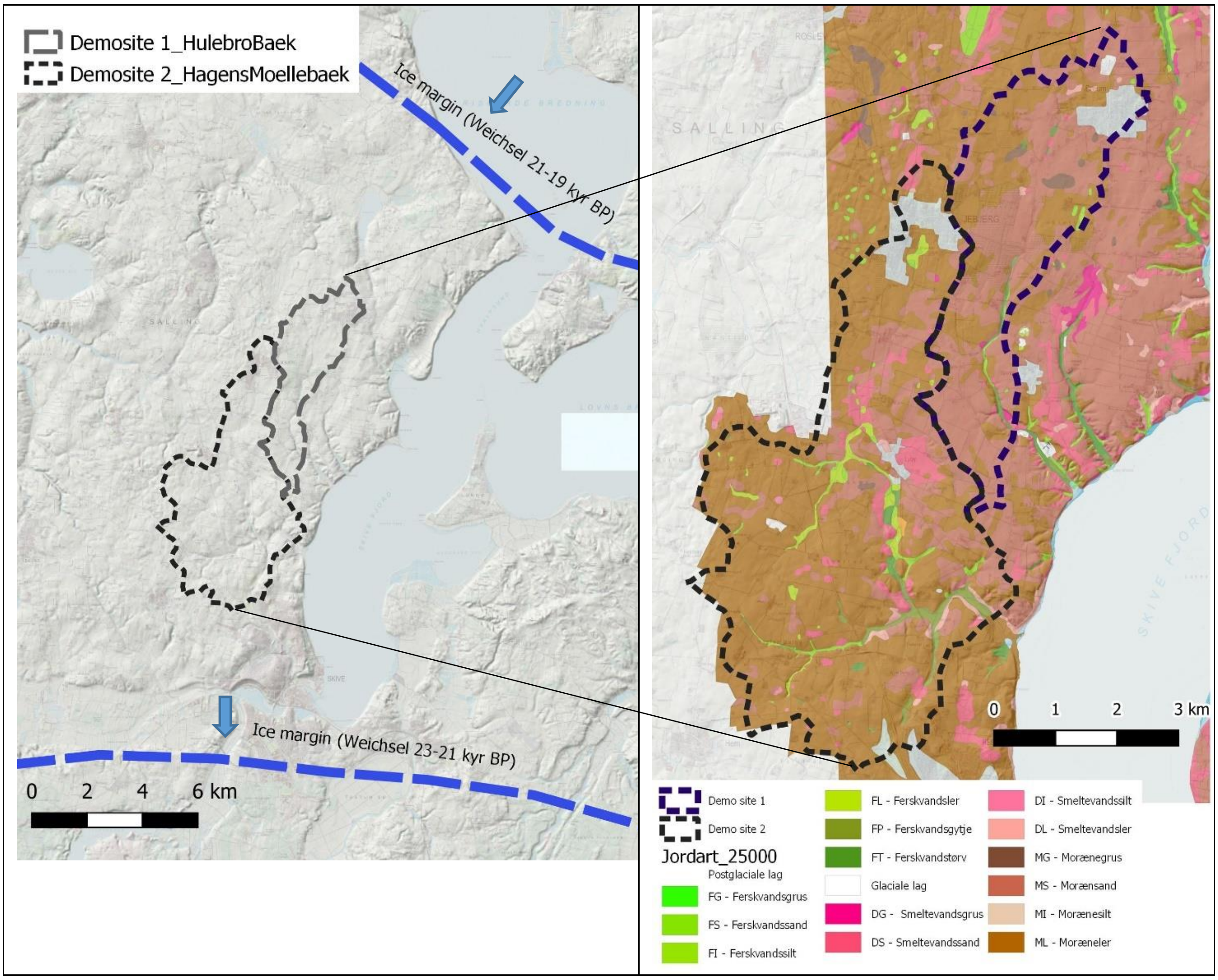


Figure 2. Left: Illustration of known ice margins during the Weichselian with ice push from north and northeast (Schack Pedersen, 1995). Right: Surface geology map (1:25.000) describing soil types in the uppermost meter (Jakobsen & Tougaard 2020). Brown colours: Tills; Red: Meltwater sand; Green: Postglacial freshwater deposits (gyttja and clay).

2 Geophysical data and boreholes

Three types of geophysical data have been collected in and around the two demo sites (see Figure 3):

a. Tow-TEM data (tTEM) shown as small purple points
b. TEM40 data (ground-based Transient Electro Magnetic soundings) shown as red points
c. MEP data (Multi Electrode Profiling) shown as green triangles/lines
d. The geological data comprise boreholes from the Jupiter database (black dots).

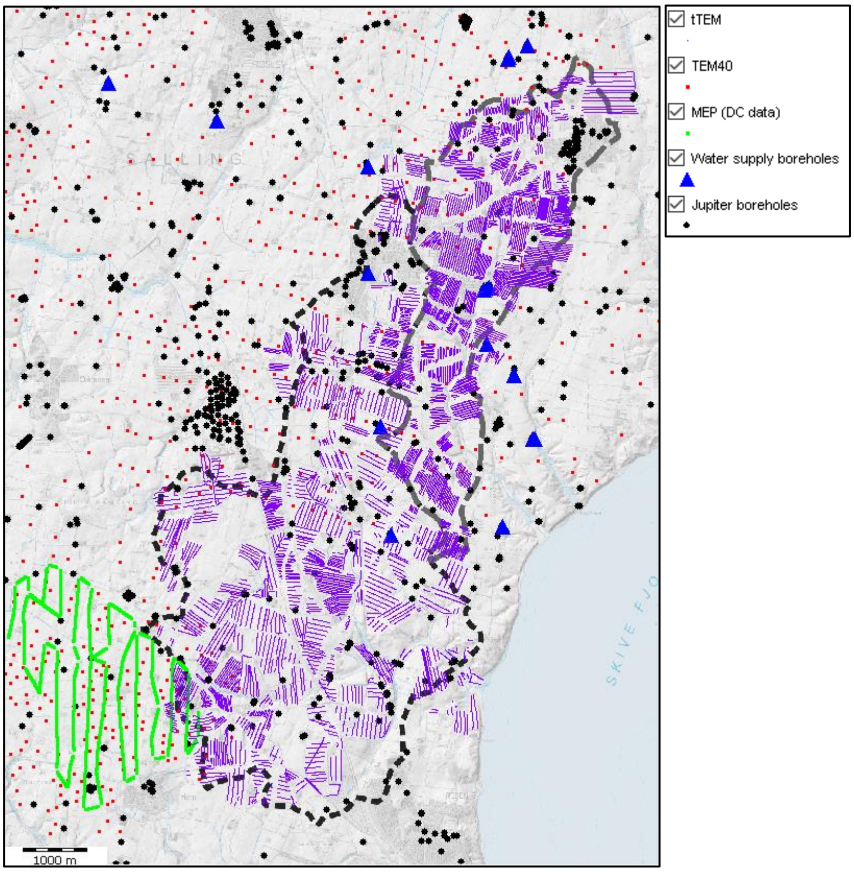


Figure 3. Boreholes (Jupiter) and geophysical datasets in the area. Legend is shown to the right. Demo site 1: grey polylines. Demo site 2: black polylines

As part of the national groundwater mapping, several ground based TEM40 soundings were 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 40-55 m. The MEP data has only been partly used in the preliminary interpretation, mainly because the data are located outside demo site 2 to the southwest (see Figure 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 3 shows the total available tTEM soundings after the geophysical data processing. The line spacing for the second data acquisition is 20-30 m.

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

3 Stratigraphy

Pre-Quaternary

From a regional perspective, the subsurface in Salling is strongly affected by both doming salt diapirs and deep-seated faults. An NNE to SSW oriented fault system is found in the area, see (Figure 4, left) and is likely to have influenced the orientation of older buried valley systems (see section 4 on buried valleys). Upward movement of the Batum salt diapir in the northern part of Salling, see (Figure 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 are deformed. Erosion of geological layers younger than the chalk deposits is also a consequence of the upward movement of the diapir.

Figure 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 initiating 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 seems less intense and not obvious in the topography.

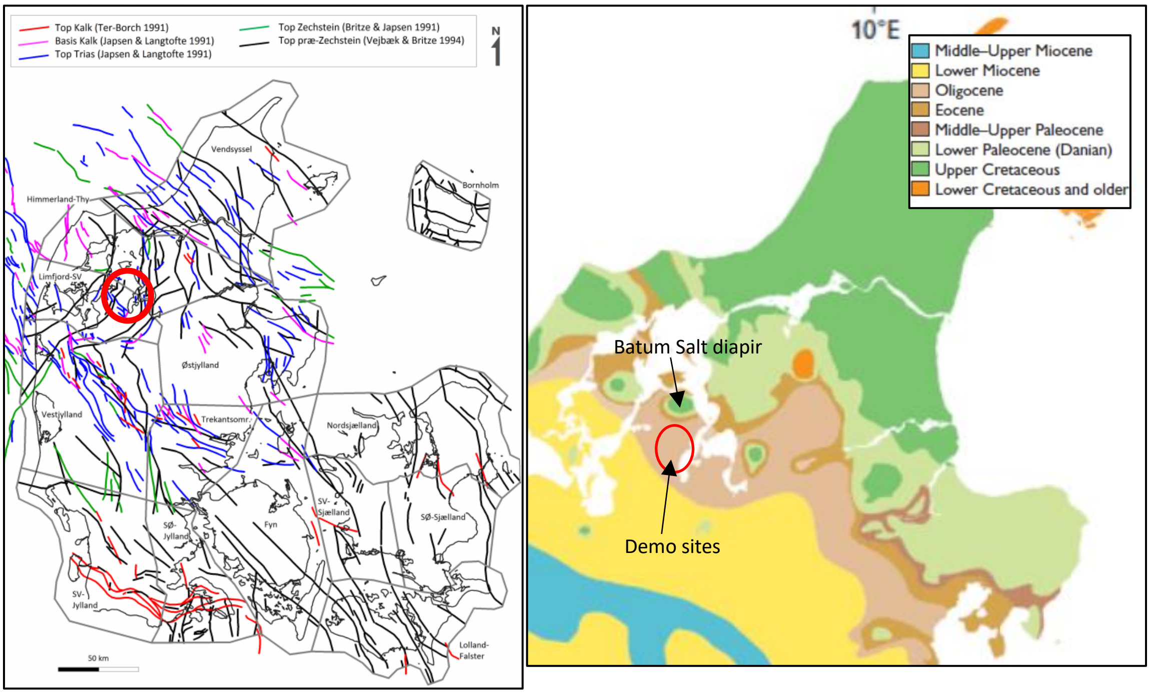


Figure 4. Left: Deep-seated fault lines in Denmark (from Sandersen & Jørgensen, 2016), red circle: Location of demo sites. Right: Pre-Quaternary surface of the northern part of Jutland (from Rasmussen et al. 2010). Red circle: location of demo sites. The Batum salt diapir is marked with an arrow.

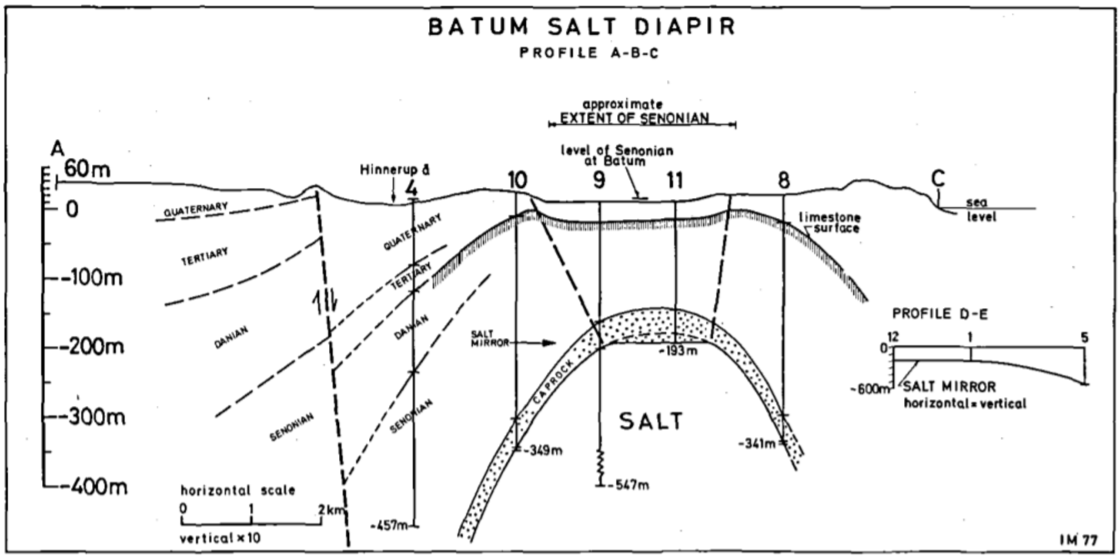


Figure 5. Sketched South (A) - North (B) profile across the Batum salt diapir illustrating the displacement of the surrounding deposits. The interpretation of fault lines is based on the deep boreholes (numbered vertical lines) in the area (Madirazza 1978).

The top of the pre-Quaternary 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). 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 geophysics. 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.

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 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). 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. 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.

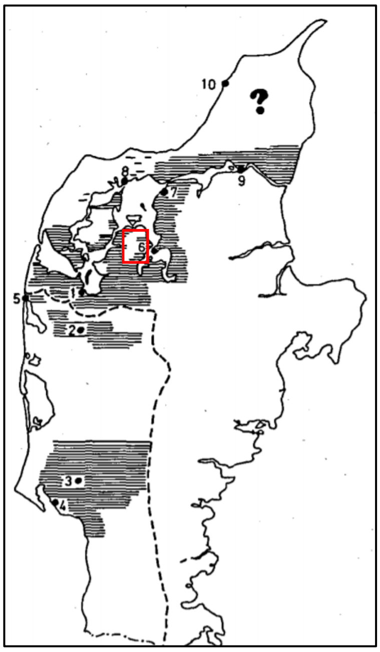


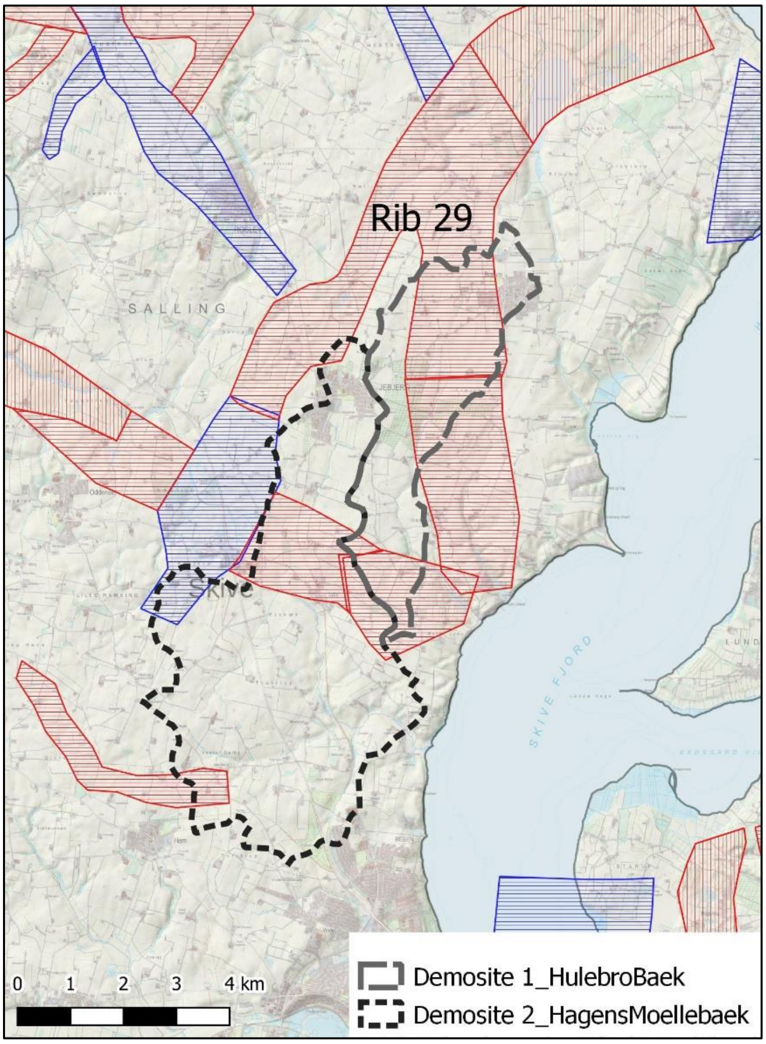
Figure 6. Interpreted distribution of regional late Elsterian to Holsteinian meltwater clays analyzed at different locations. From Jensen (1984). The Salling area is marked with a red rectangle.

4 Buried tunnel valleys

The Salling peninsula is cross cut by several buried valleys with different orientations and age. Figure 7 shows the buried valleys mapped within the two demo sites based on existing TEM40 soundings from the National groundwater mapping program 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 possible 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. 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 creeks have the same orientations as the valley systems.



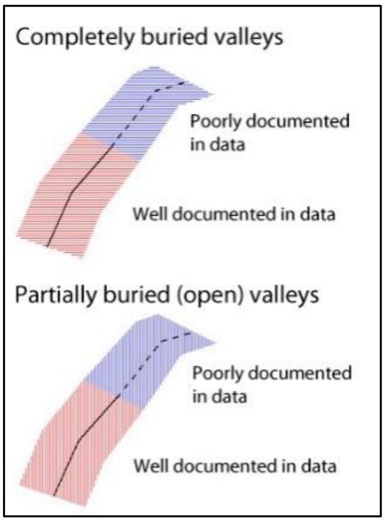


Figure 7. Mapped buried valleys close to the study area (shown with black hatched line). Legend for the map is shown above (Sandersen & Jørgensen, 2016) and on www.buriedvalleys.dk)

5 Geological interpretation of geophysical data (both demo sites)

Demo site 1 and 2 are described mutually 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 surface 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 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, TEM40 soundings are shown on Figure 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.

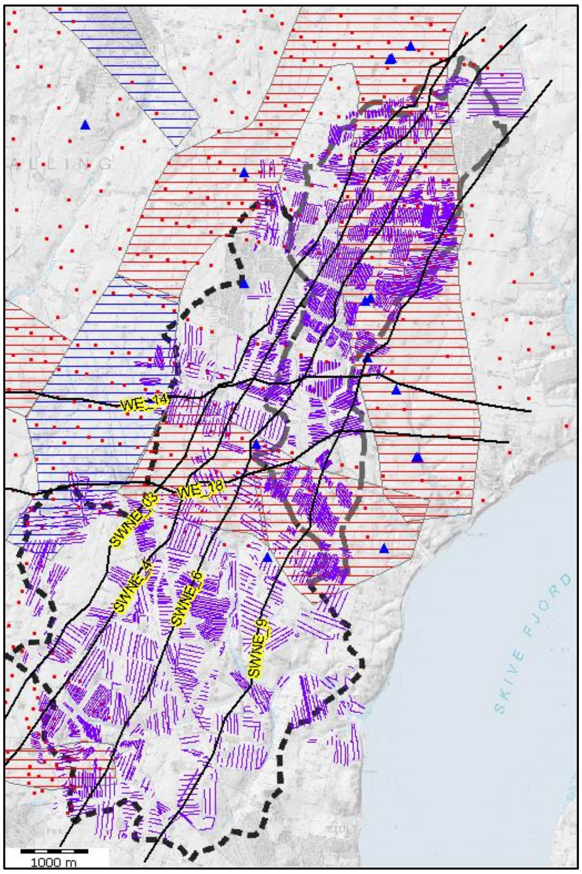


Figure 8. Cross-section overview. Cross-sections: Black lines with yellow labels. Red and blue shaded polygons represent mapped buried valleys (see Figure 7; Sandersen & Jørgensen, 2016). Purple point: tTEM data, red points: TEM40 soundings, Water supply wells: blue triangles

In the following, the geological interpretations performed on the cross-sections (shown in Figure 8) and on four selected 2D resistivity maps are presented (Figure 9 and Figure 10). The Depth of Investigation (DOI) for the tTEM data is shown on the cross sections with thin, dashed grey lines.

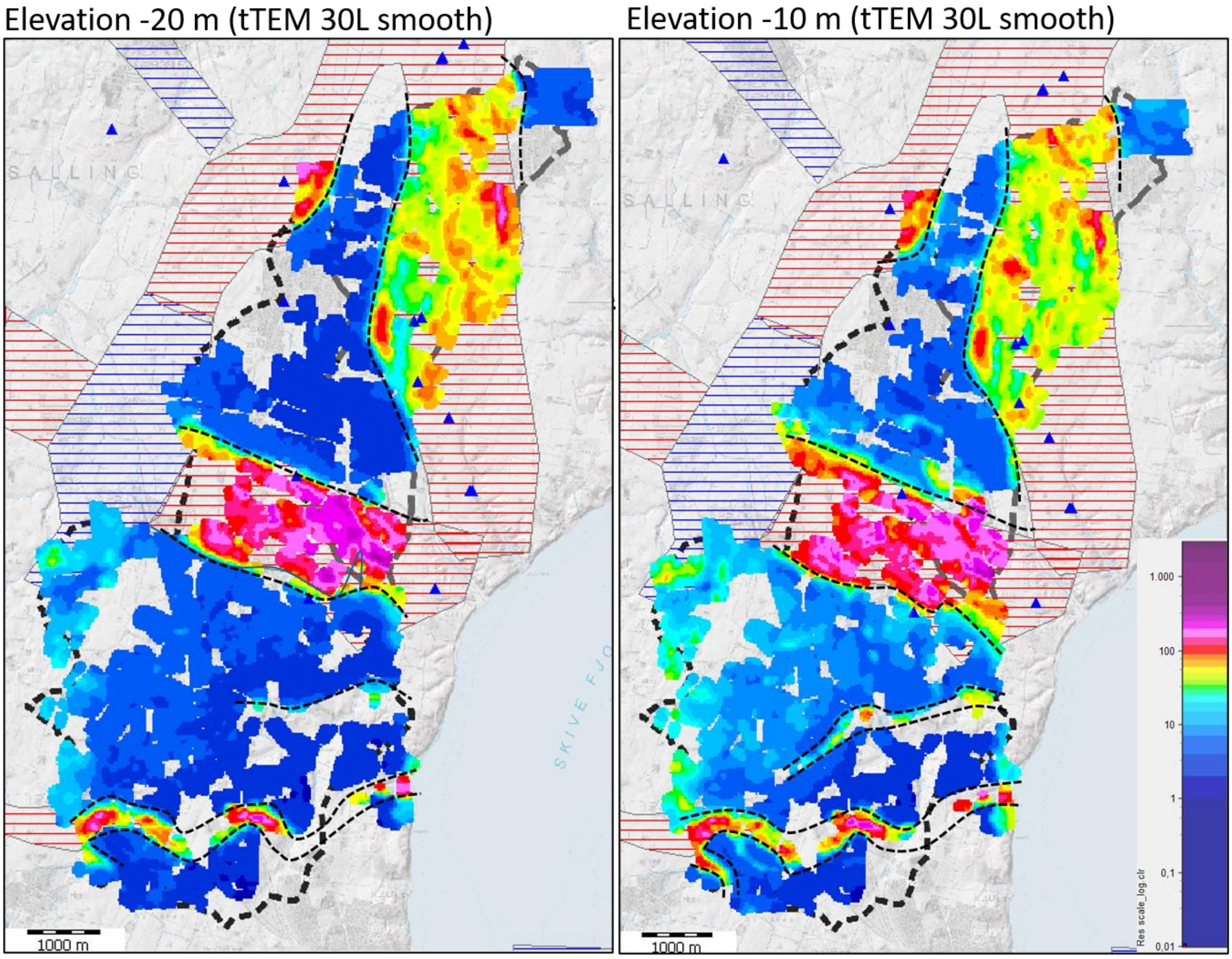


Figure 9. Interpolated resistivity slices (Grid cells 25x25x1 m) for elevation -20 m and -10 m. Dashed lines indicate buried valleys interpreted from tTEM data. Blue colours represent clays and red colours indicate sand to gravel.

Figure 9 shows two slices of tTEM 3D resistivity grids with an underlying theme of earlier mapped buried valleys. at the elevations -20 m and -10 m. 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 clays and meltwater sands. 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, two narrow E-W valleys are identified cross-cutting Miocene and Oligocene deposits to the south (see Figure 9).

Figure 10 gives an overview of the slices at elevation -2 m and +10 m. 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 a eastern to north-eastern icepush.

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. 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 10, right). Also, these smaller valley systems can be followed close to the terrain.

On both resistivity maps on Figure 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.

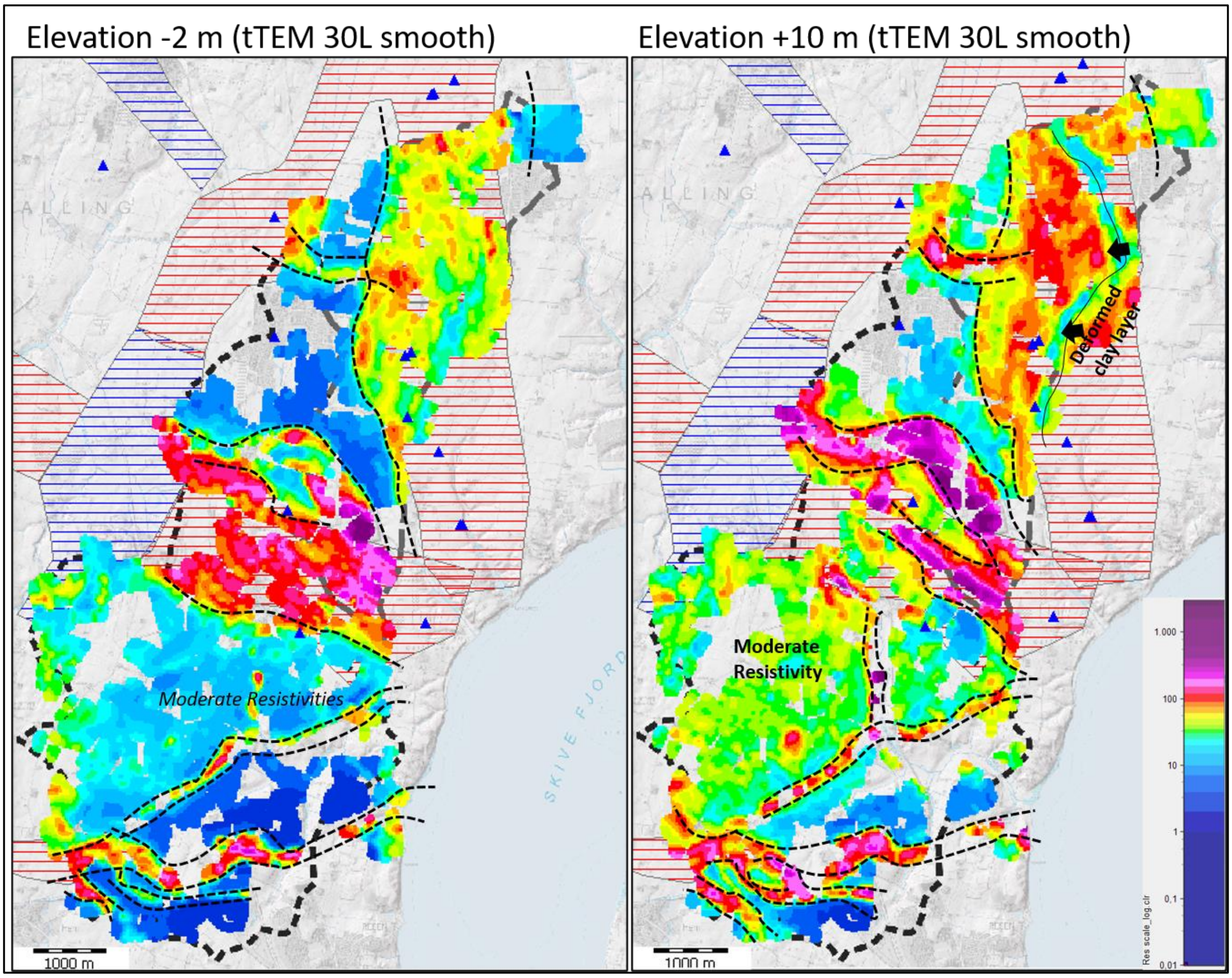


Figure 10. Interpolated resistivity slices (Grid cells 25x25x1 m) for elevation -2 m and +10 m. Dashed lines indicate buried valleys interpreted from tTEM data.

Cross-section SWNE_03 (Figure 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 geophysics in all of the area - going from moderate and high resistivities (Quaternary deposit and to a smaller degree Miocene deposits) to resistivities below 10 Ωm (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).

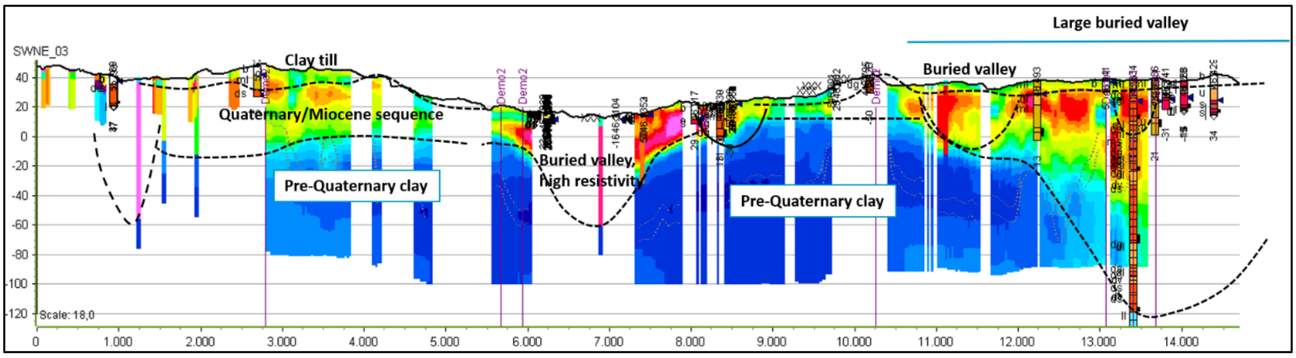


Figure 11. Cross-section SWNE_03, southwest to northeast. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The wide N-S buried valley is interpreted on cross-section SWNE_4 (Figure 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 10).

At 6000-9000 m (Figure 12) the profile crosses the more 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.

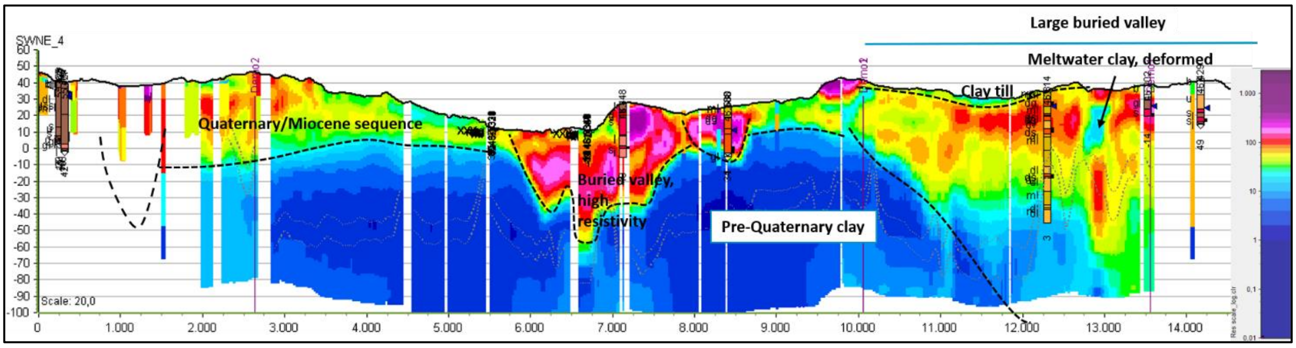


Figure 12. Cross-section SWNE_4, Southwest to northeast. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section in Figure 13 (SWNE_06) also crosses both demo sites southwest to northeast, see location on Figure 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 or less, and d) a lower boundary to the marine, pre-Quaternary clay.

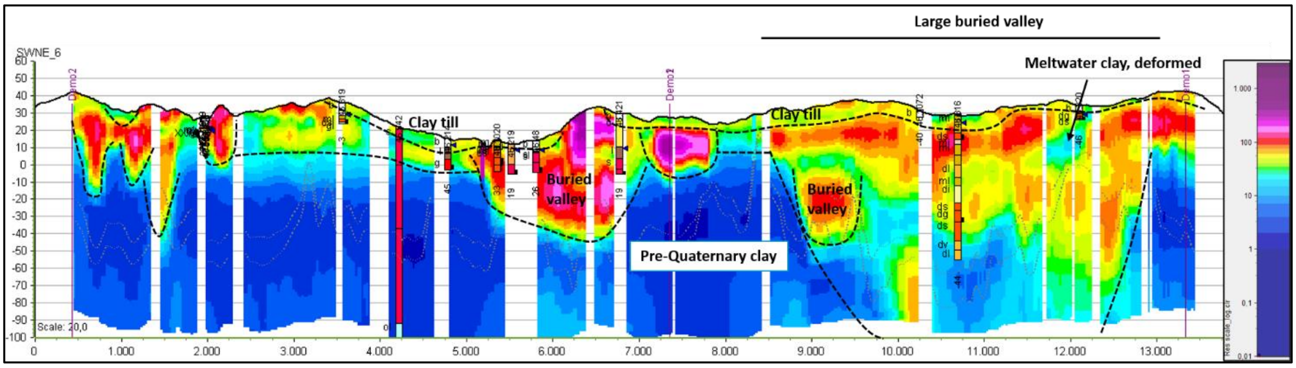


Figure 13. Cross-section SWNE_6, southwest to northeast. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section SWNE_9 in Figure 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 parts 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.

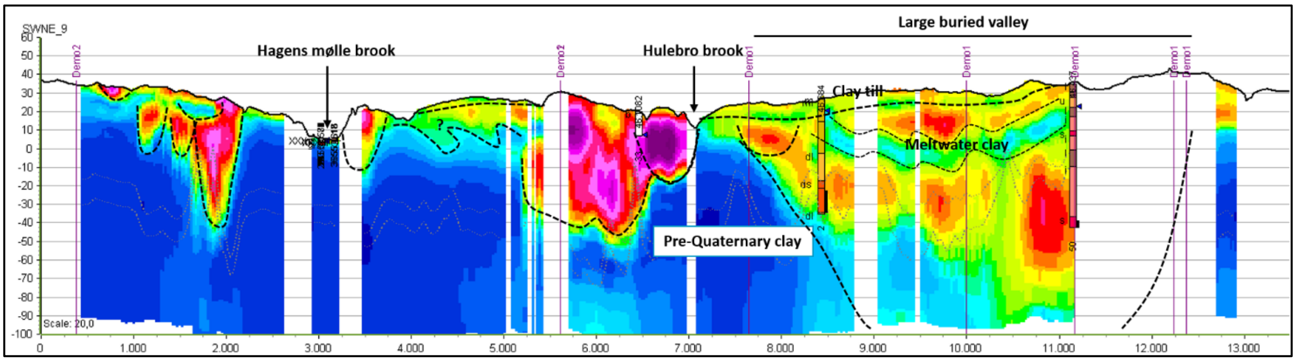


Figure 14. Cross-section SWNE_9, southwest to northeast. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Cross-section WE_14 (Figure 15) is a west-east oriented cross-section following the valley of rather high resistivities eroded down to elevation -10 to -25 m 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.

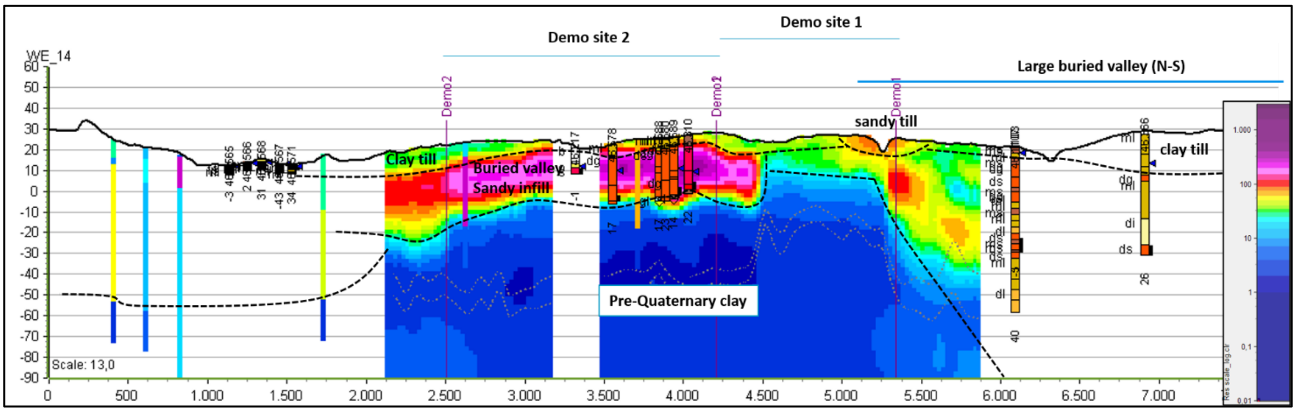


Figure 15. Cross-section WE_14, west to east. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

The cross-section WE_18 (Figure 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.

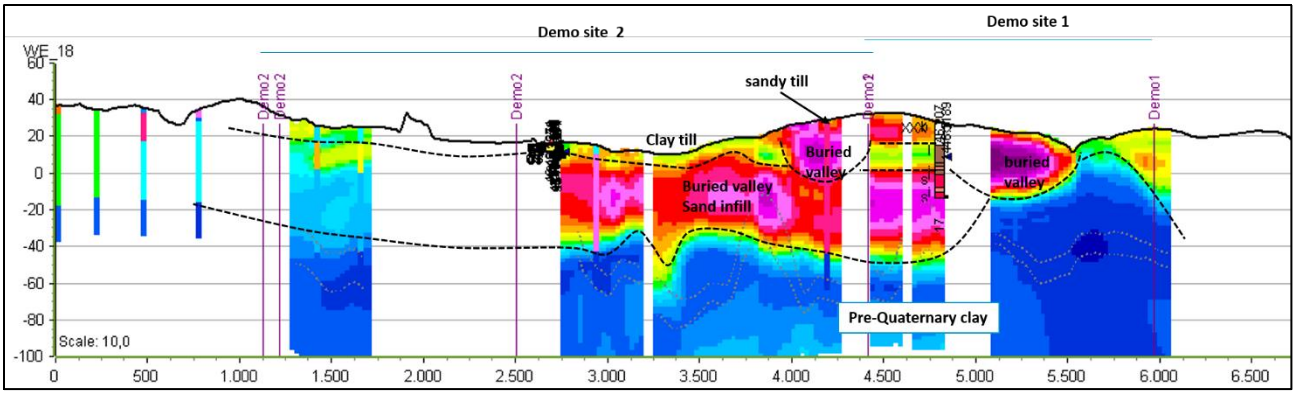


Figure 16. Cross-section WE_18, west to east. For location, see Figure 8. TTEM data are shown as a 3D resistivity grid. TEM40 data are visualized as single sounding poles. Thin grey lines represent upper and lower DOI of tTEM data.

Finally, on Figure 17 is a 2D overview of the elevation of 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.

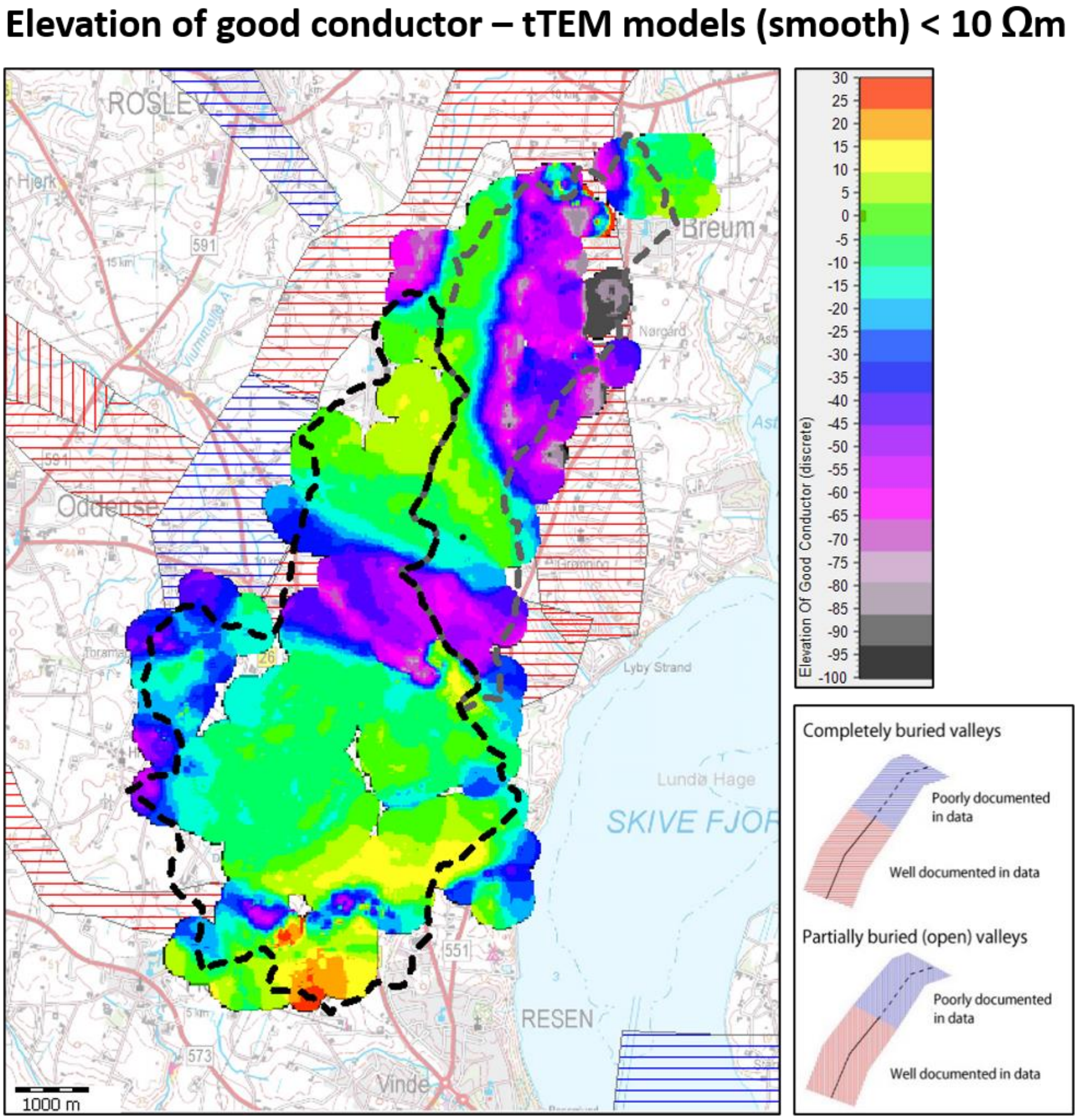


Figure 17. Elevation of good conductor in tTEM data. The criterion is that the deep low-resistive layer in the smooth tTEM models must be < 10 Ωm.

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

1) **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 in boreholes. The geological element stand out as a low resistivity volume, is well defined, and is found very close to the surface in areas where the clays have not been eroded by Quaternary erosion.
2) **GE2: Two W-E oriented buried valleys**
GE2 contains of 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 of proposedly same generation with a width of 350 m is included in GE2. The valleys are dominated by high resistivities in the TEM models (> 100 Ωm) and eroded down to elevations of -40 to -50 m.
3) **GE3: N-S oriented buried valley**
N-S oriented valley system in a large part of demo site 1. Within the large valley, the deeper parts is interpreted to have infill of meltwater sand and clay. An expected Elsterian meltwater clay layer is identified in the valley and elevations around 0 m. The clay unit is be heavily glaciotectonic deformed.
4) **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, 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 18 below:

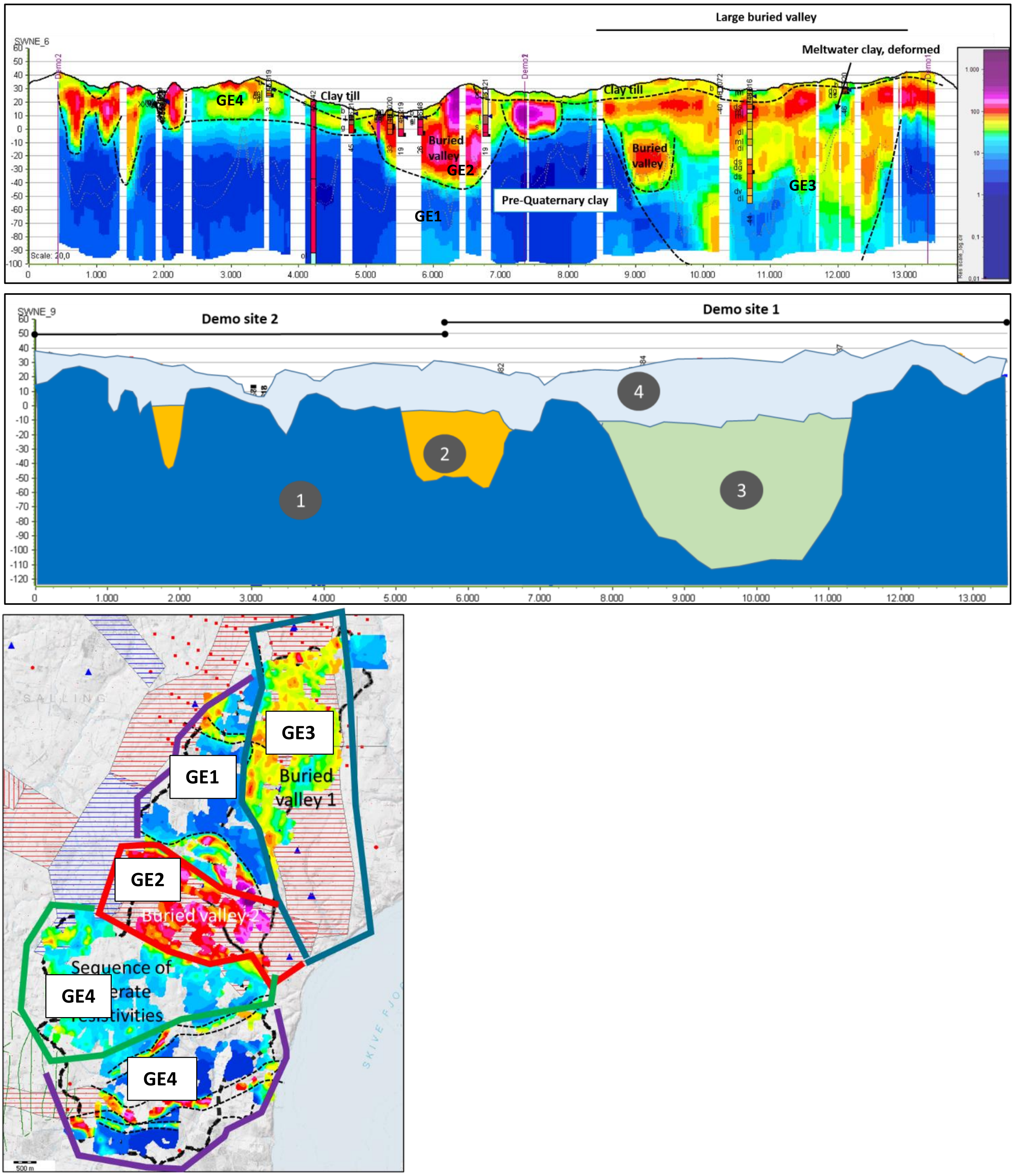


Figure 18. Top figures: Cross-sections showing the outlined geological elements described in the text. Bottom figure: Map view of the different geological elements dominating the two demo sites.

6 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 geophysics, 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.

a. **Geological interpretation and correlation:** The demo sites are characterized by a clay-dominated moraine landscape from the last glaciation (The Weichselian) with occurrences of postglacial deposits in low-lying areas. Sediments are clay tills, meltwater clays, 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.

7 References

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