DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2023/44**

N-retention tTEM mapping: Preliminary geological interpretations in the Villestrup-area

Peter B.E. Sandersen

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1. Foreword

This report is made as a part of the N-retention project for the Danish EPA (see GEUS, 2022) and covers the preliminary geological interpretations in the Villestrup area in northern Jutland (Figure 1.1).

The purpose of the interpretations is to establish a conceptual geological understanding of the structural setting and the sedimentary succession within the area. The geological interpretations are primarily based on newly collected tTEM data related to the N-retention-project (WSP, 2023) and existing data from the national geophysical database Gerda and the national borehole database Jupiter (see www.geus.dk). The geological interpretations can be used as input for further geological modelling.

Figure 1.1: Location of the Villestrup area.

2. Geomorphology and topography

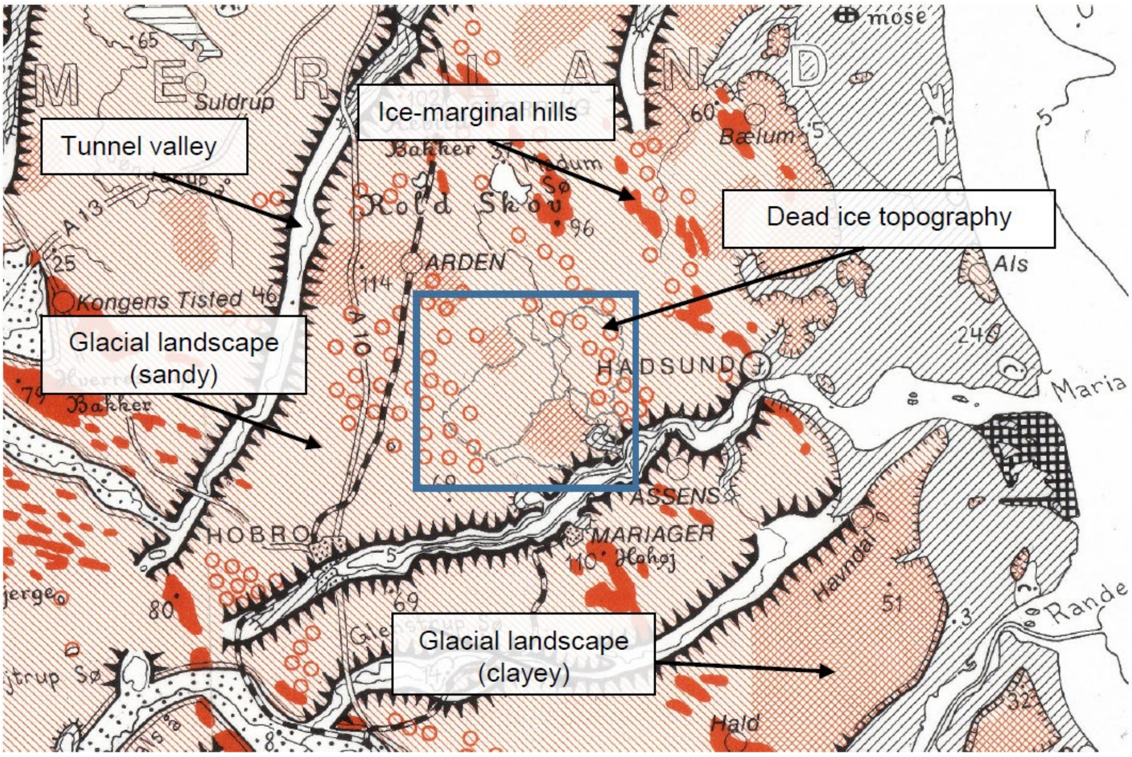

Figure 2.1: Geomorphological map. The outline of the mapped Villestrup area is shown with grey lines inside the blue rectangle. An elevation map for the area inside the blue rectangle is shown in Fig. 2.2. Map width is approx. 50 km. (Base map from Smed, 1979).

The Villestrup study area (Figure 1.1 and Figure 2.1) is located in a glacial landscape in northern Jutland just north of Mariager Fjord between the towns of Hobro and Hadsund. In and around the study area, the glacial terrain is predominantly sandy and characterized by presence of prominent open tunnel valleys, dead ice topography, and ice-marginal hills. The tunnel valleys are oriented between NNE-SSW and ENE-WSW, and the areas with dead-ice topography and the ice-marginal hills are roughly oriented perpendicular to the valleys.

The western part of the study area is hilly, reaching elevations of around 50-100 m above sea level (a.s.l.), whereas the central and eastern parts lie below 50 m a.s.l. (Figure 2.2). Along all of the eastern border, the rather low, N-S oriented and irregular hilly area is interpreted on Figure 2.1 as dead-ice topography. Hills like these are also found north of the study area, and they probably represent temporary ice margins as described by Lerche et al. (2014).

The central and eastern parts of the study area show topographic valleys with dominating orientations between SW-NE and NW-SE/NNW-SSE.

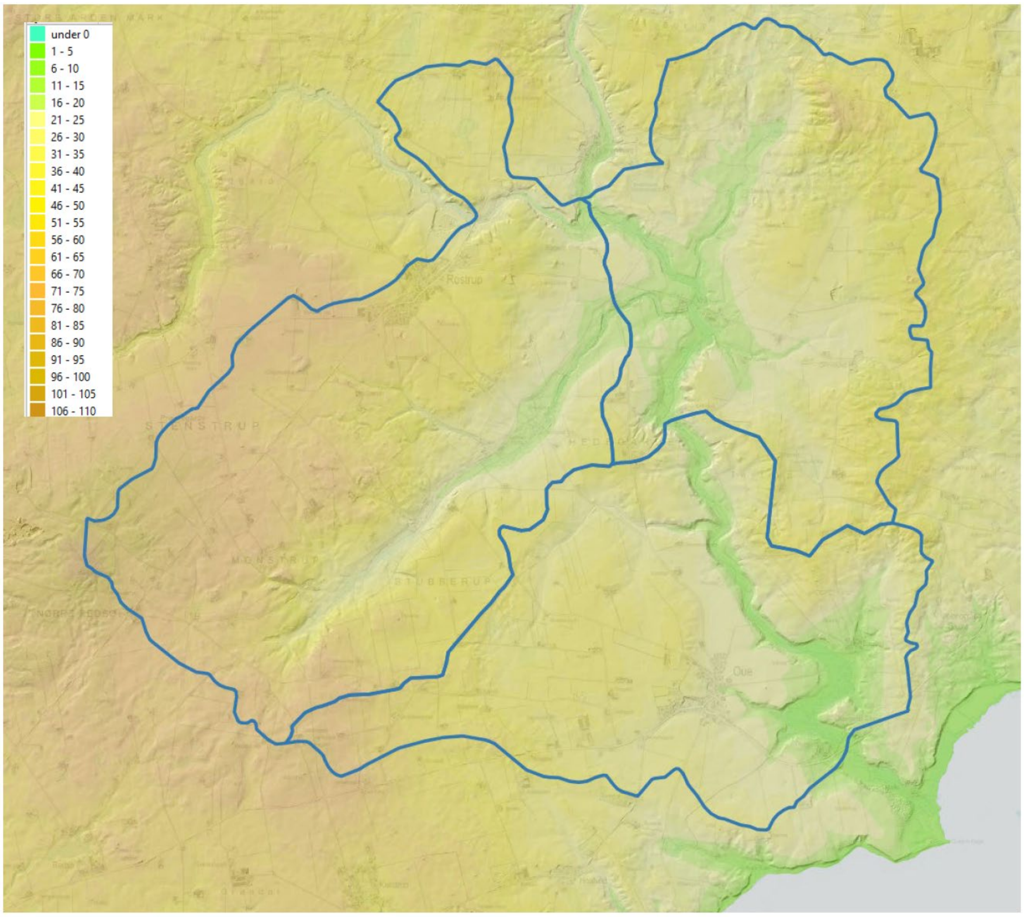

Figure 2.2: Elevation map (National Digital Elevation Map). The ID15 catchments within the study area is outlined with blue lines. The blue area to the southeast is Mariager Fjord. See also Figure 2.1.

3. Structural framework

The study area is located in the northern part of Denmark at the southern margin of the Sorgenfrei-Tornquist zone (Figure 3.1). The Sorgenfrei-Tornquist Zone (STZ) in northern Denmark is interpreted as a tectonic structure separating the Danish Basin from the Fennoscandian Shield (Hansen et al., 2000). The STZ is a deep-seated fault zone between two crustal block areas and it is bounded by the Fjerritslev Fault to the south and by the Børglum fault to the north (Figure 3.1). The STZ was formed in the Precambrian and the structure has been tectonically active for millions of years until the Late Glacial and is considered active even to the present day (Brandes et al. 2018; 2022; Gaidzik & Kázmér, 2023; Mogensen and Korstgård, 2003).

The Villestrup area is located within the Sorgenfrei-Tornquist zone and faults with orientations between NW-SE to N-S are expected to predominate (Figure 3.1).

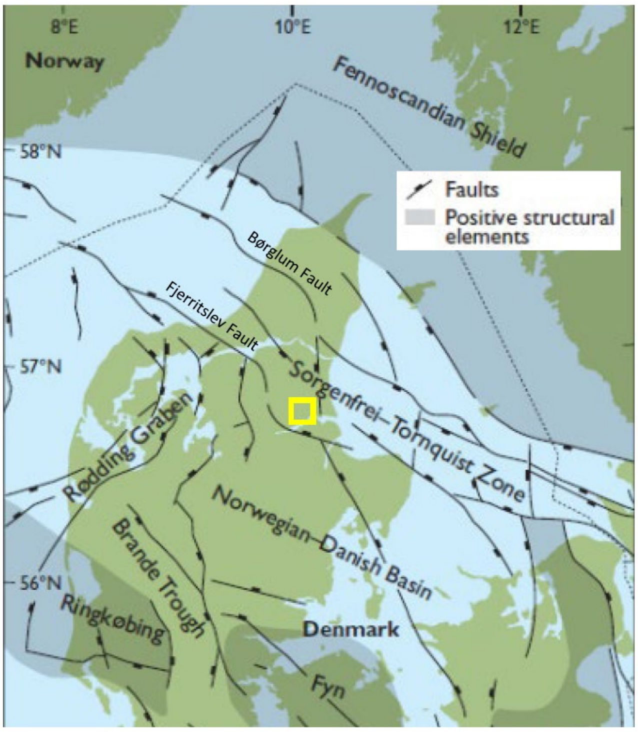

Figure 3.1: Deep-seated tectonic structures in northern Denmark (modified after Rasmussen et al. 2010). The Villestrup area is marked with a yellow rectangle.

4. The sedimentary succession

4.1 Pre-Quaternary sediments

The map in Figure 4.1 shows that the uppermost pre-Quaternary sediments within the study area are from the Lower Paleocene (Danian) and Upper Cretaceous. The pre-Quaternary deposits comprise Danian limestone and Cretaceous (Maastrichtian) chalk below. The Danian Limestone is up to 50 m thick and generally the pre-Quaternary succession dips in a southwesterly direction (Thomsen, 1995). Palaeogene clays can be found on top of the Danian limestone west of the study area, but local downfaulted occurrences of these clays might be found close to the study area.

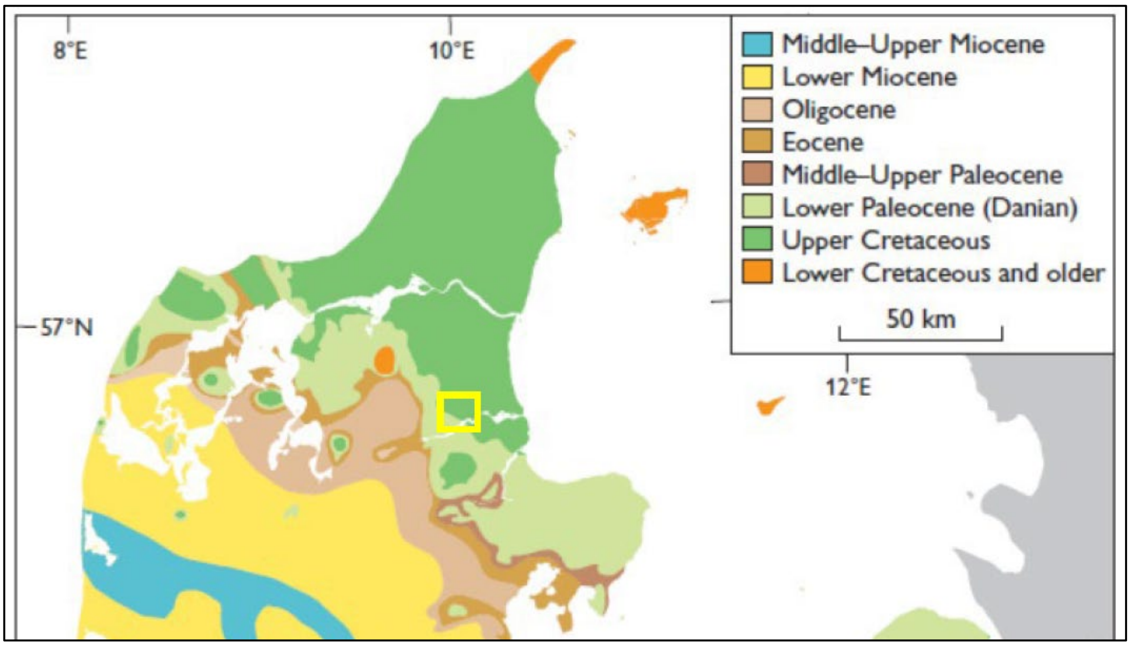

Figure 4.1: Pre-Quaternary sediments in the northern part of Denmark (modified from Rasmussen et al. 2010).

Boreholes within the study area usually describe the Cretaceous chalk as white to greyish white, soft, and containing some flint (e.g. DGU no. 49.2288; 49.668). In some boreholes, however, the chalk is described as hard to very hard. Usually there is not much more information in the lithological descriptions, but in DGU no. 49.1033, approx. 11 m below the top of the chalk, there is a mention of 'veneers of clay'. This could be the Upper Maastrichtian 'Rørdal Member', which has been described as a 10 to 30 m thick succession of alternating marls and chalk in quarries in Ålborg and in boreholes in eastern Denmark respectively (Surlyk et al., 2010; Schovsbo et al. 2008). In Ålborg, north of the Villestrup area, the Rørdal Member is seen as 8 individual marl layers a few meters below the top of the Maastrichtian (Surlyk et al., 2010).

The Danian limestone above is described as white to greyish white, hard to very hard, and typically containing much flint (e.g. DGU no. 49.668).

4.2 Quaternary sediments

The youngest ice-advances of the last ice age that reached the area was the ‘Kattegat advance’ from the north (29-27.000 years ago; Figure 4.2A), the ‘Main ice advance’ from northeast (23-21.000 years ago; Figure 4.2B), and finally a re-advance from the east (C: 19.000 years ago; Figure 4.2C; Larsen et al., 2009). These ice advances are considered responsible for many of the geomorphological features and the uppermost sediments in eastern Himmerland.

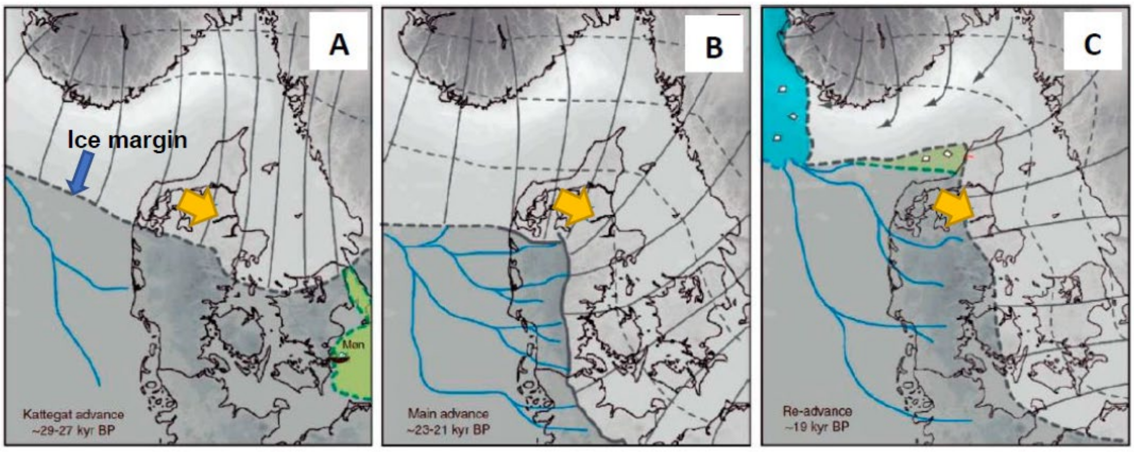

Figure 4.2: Main ice-marginal positions during the Late Weichselian: A) The Kattegat advance, B) The Main advance and C) Re-advance during the general recession of the Main advance. The orange coloured arrow marks the study area. Modified from Larsen et al. (2009).

The surface geology in the uppermost meter of the study area is dominated by Quaternary sediments in the form of meltwater sand with patches of clay tills and sandy tills (Figure 4.3). Postglacial freshwater sand can be found in the low-lying areas.

This matches the information from boreholes from which samples of meltwater gravel, silt and clay can be added to the list. The Quaternary sediments – apart from the uppermost few meters – generally contain calcium. The Quaternary succession varies in thickness from more than 100 m in buried valleys to a few meters on top of the pre-Quaternary chalk and limestone.

In borehole DGU no. 49.535, located in a deep buried valley (see later description) in the southeastern part of the study area, the 127 m thick Quaternary succession is dominated by meltwater clay with minor occurrences of clay till and meltwater sand. Thick clay-dominated successions like this are only seen in a limited number of boreholes. As mentioned in the preceding, several ice advances have reached the area resulting in a complex Quaternary stratigraphy due to glaciotectonic deformation and erosion (e.g. Houmark-Nielsen, 2005), and for instance there are signs in previous subsurface mapping, that the infill of the buried valley is deformed (Sandersen & Jørgensen 2016).

Generally, the boreholes in and around the study area provide enough lithological information to give a good impression of the variations in the Quaternary sedimentary succession. However, because of the often very thin Quaternary sediment cover and a high degree of deformation correlations between boreholes may be difficult to perform.

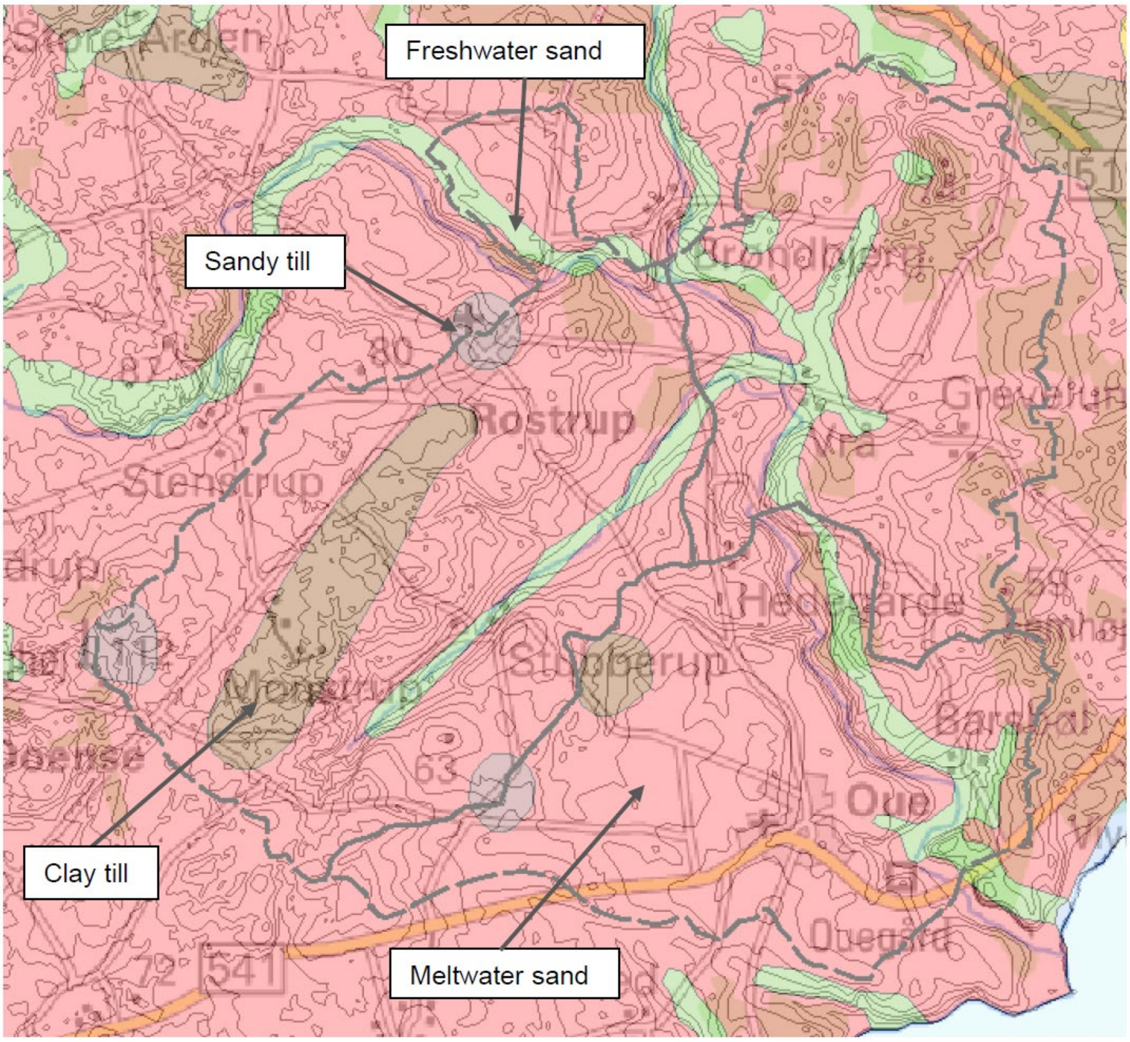

Figure 4.3: Surface geology (the uppermost meter; Jakobsen & Tougaard, 2020). Grey broken line marks the study area.

5. Buried tunnel valleys

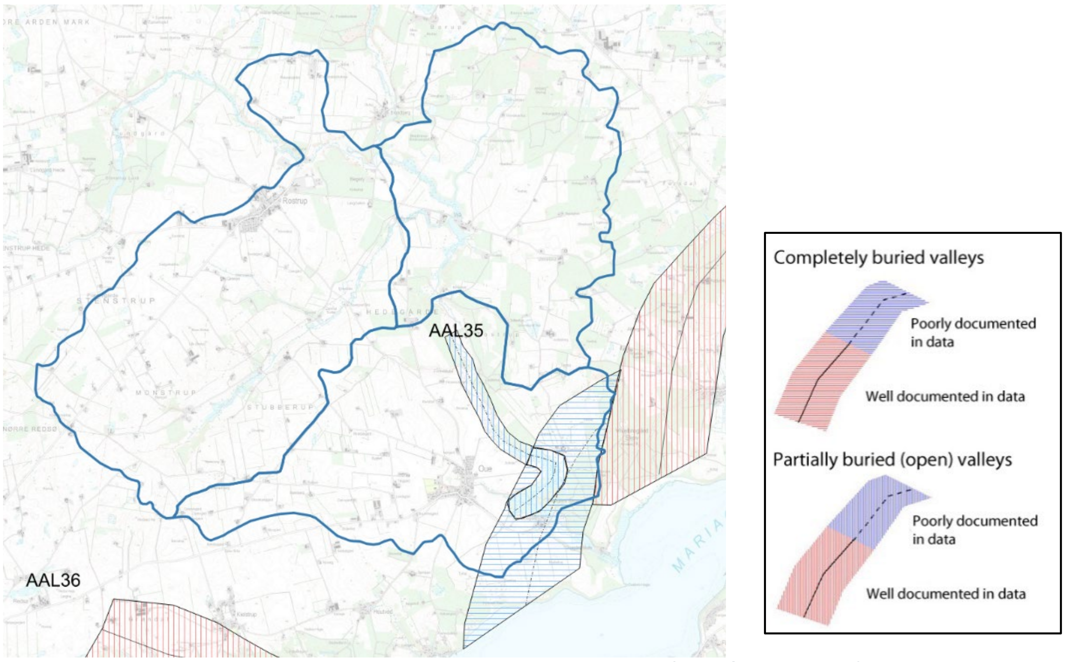

Figure 5.1: Buried valleys mapped within the study area (data from Sandersen & Jørgensen, 2016). The label AAL35 refers to locality numbers used in Sandersen & Jørgensen and www.buriedvalleys.dk.

Figure 5.1 shows the buried valleys that have been mapped in the south-eastern part of the study area. The valleys are generally formed as tunnel valleys by meltwater underneath the ice sheets during the Pleistocene glaciations (Sandersen & Jørgensen, 2016).

The two buried valleys east of the village Oue to the south, are 'poorly documented' because the previously available data (SkyTEM and boreholes) were able to map the presence of the valleys and their orientation, but the outline was uncertain (Sandersen & Jørgensen, 2016). The broadest valley is oriented NNE-SSW and around 1,5 km wide and it was seen in SkyTEM data as low resistivities in a depth interval spanning more than 50 m. The low resistivities matched the thick clay layers found in borehole DGU 49.535 (see above). High resistivities in the upper parts of the valley suggested a high silt content. The buried valley is eroded into the Maastrichtian chalk and is 100 m deep or more. A 250-400 m broad and in general NNW-SSE oriented buried valley northeast of Oue has low SkyTEM resistivities between 10 m a.s.l. and 15 m b.s.l. Low resistivities below this depth, are seen in SkyTEM data pointing to saline porewater. According to Sandersen & Jørgensen (2016), it appears as if there is a fault below the valley.

6. Geophysical data and boreholes

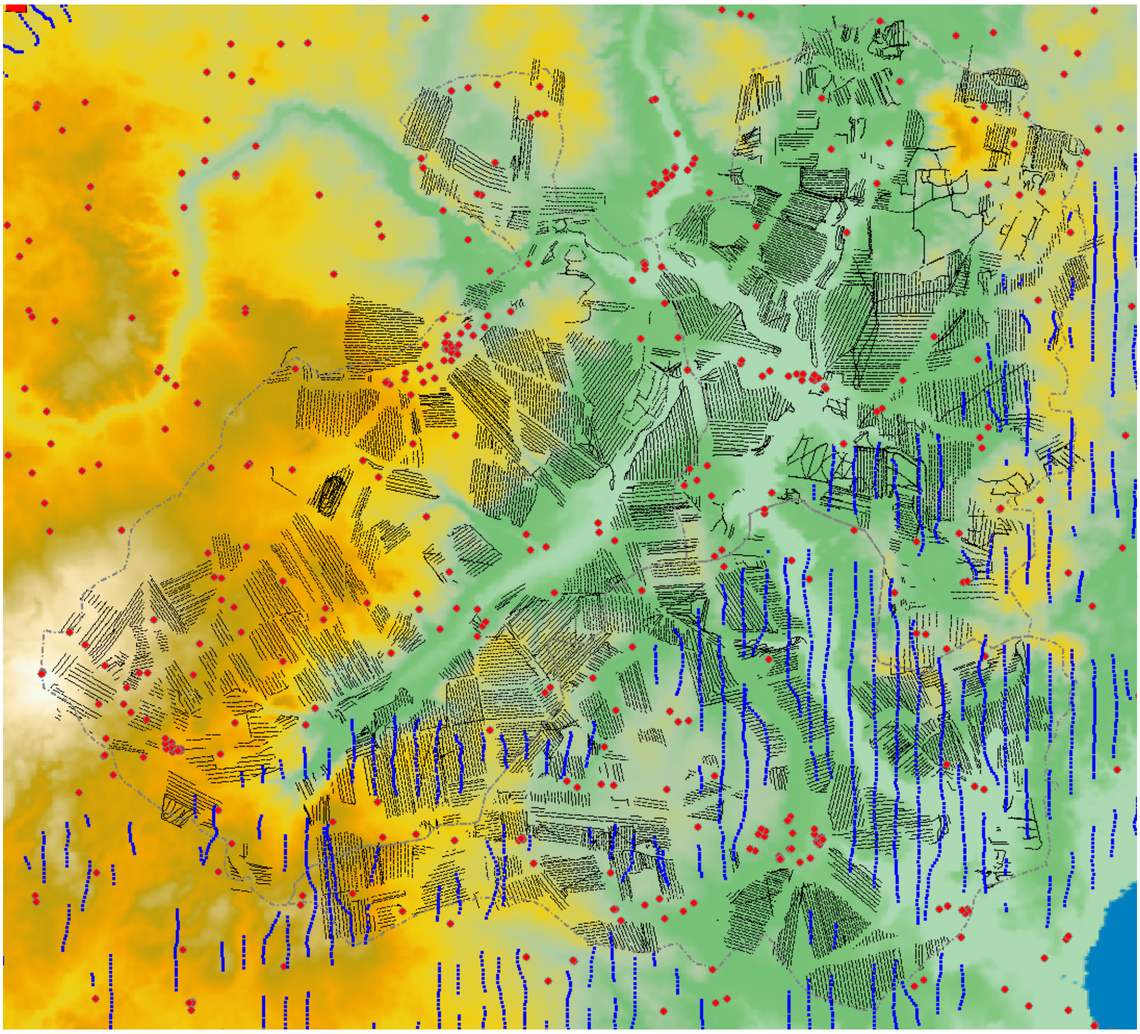

Figure 6.1: Geophysical data and boreholes. tTEM soundings are shown as small black dots, SkyTEM is shown as blue dots and Jupiter boreholes are shown as red dots. TEM data are from the Gerda database and borehole data from the Jupiter database (www.geus.dk). Background map shown terrain elevation (Brown: high elevations; light green: low elevations.

Three types of geophysical data have been collected in and just around the study area (Figure 6.1):

New geophysical data collected in N-retention project:

- tTEM data (black lines) (WSP, 2023)

Existing geophysical data:

- TEM data (Transient Electro Magnetic method; blue dots)
- Seismic data along the road through the town of Oue in the southern part of the study area (not shown on Figure 6.1)

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

Both smooth and sharp inversions of the tTEM data have been used in the geological interpretations, but only the smooth inversion is shown on the profiles in the following. Further description of the data will not be provided in this report. More information about the tTEM survey and the data processing can be found in the geophysical data report (WSP, 2023). The seismic data has been used in connection with the previous interpretations of buried valleys close to Mariager Fjord (Sandersen & Jørgensen, 2016), and because of the limited resolution of the upper parts of the seismic data, the data has not been used in the present study.

7. Geological interpretation of geological and geophysical data

7.1 Overview

The tTEM data, the SkyTEM in the south-eastern part, and the borehole data provide a good picture of the overall geological setting of the study area.

13 geological profiles through the tTEM data and boreholes have been produced (Figure 7.4 to Figure 7.16; location shown in Figure 7.1 and Figure 7.2; see also larger versions in Appendix 1). For simplicity, only tTEM data is included on most of the profiles alongside with borehole data. Where SkyTEM data has added information to the interpretations and in case SkyTEM data is shown on a profile, this will be mentioned in the text and in the captions. On the profiles, lithological interpretations are shown as labels and tentative geological interpretations are sketched using hatched lines for layer boundaries. Tentative faults have also been sketched on the profiles.

One selected 2 m slice of tTEM mean resistivities is shown in Figure 7.3.

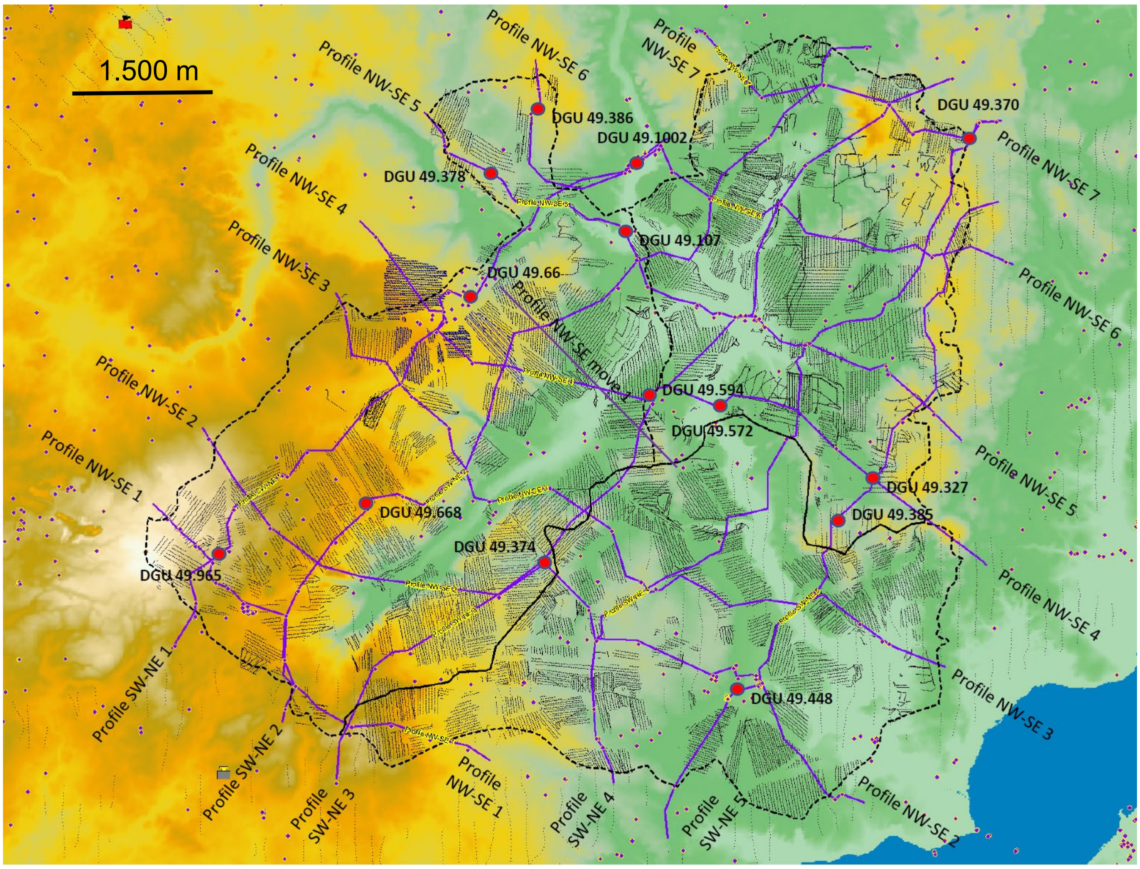

Figure 7.1: Location of profiles. tTEM soundings are shown as black dots, SkyTEM as small grey dots and boreholes as red dots. Selected boreholes are shown with larger red dots and borehole number label.

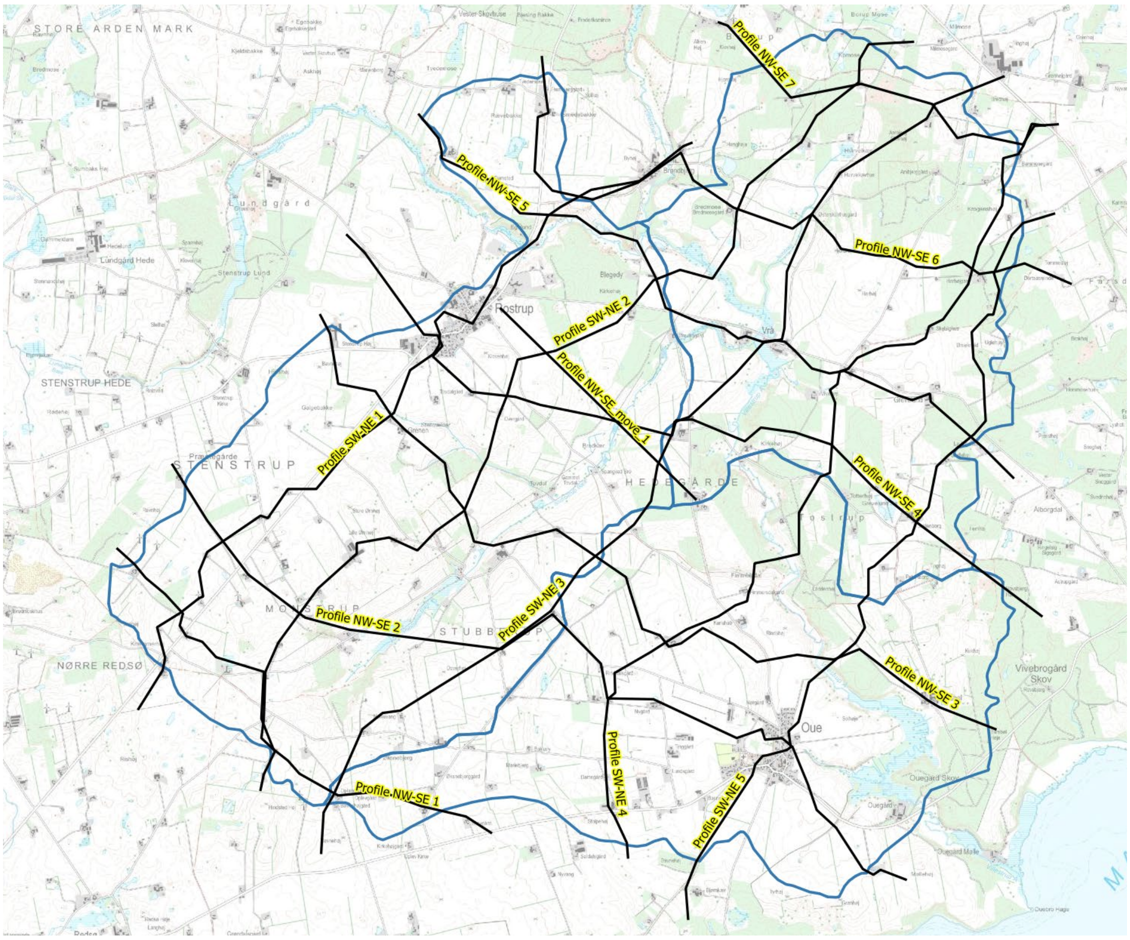

Figure 7.2: Location of profiles shown on a 1:25.000 map.

The resistivity scale used for tTEM data on the profiles and the resistivity slice is shown in Figure 7.3. On all profiles, the DOI (Depth of Investigation; lower) is shown as a grey hatched line. The DOI represents the depth below which the tTEM cannot be considered reliable. (See Christiansen et al., 2012).

Because the geological interpretations presented in the following are based on a tight co-interpretation of tTEM and borehole information, interpretations of the geology from the data are primarily presented on the vertical profiles.

Boreholes that have been selected as high priority boreholes in the project are highlighted on the profiles and on Figure 7.1 with large red dots and enlarged borehole numbers.

7.2 Mean resistivity slices

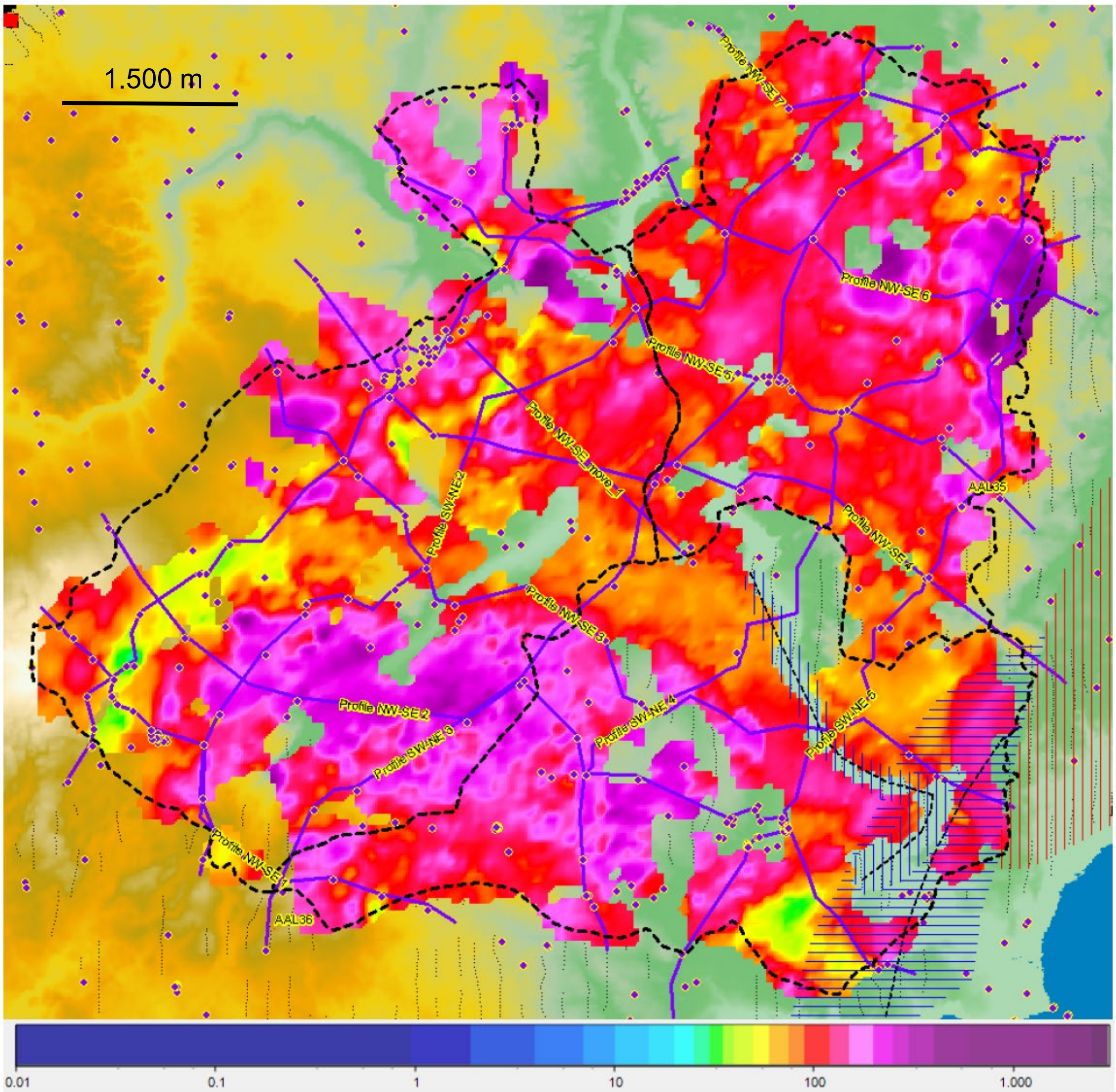

Figure 7.3: Mean resistivity slice of tTEM data; 0 m a.s.l. Resistivity scale at the bottom; in ohmm.

The 2-m mean resistivity slice from 0 m a.s.l. in Figure 7.3 shows that high electrical resistivities (red/purple colours) dominate the tTEM data in the study area, and only smaller areas with lower resistivities appear. In the Villestrup area, the mean resistivity slices are less informative than the 2D vertical profiles and therefore no further slices are presented in this report.

7.3 Vertical profiles

Of the following 12 profiles, the first 5 are running SW-NE and are more or less parallel, and the last 7 are NW-SE and likewise roughly parallel (see Figure 7.2). The profiles cross each other, and the locations where they do are shown on the individual profiles as vertical blue lines with the name of the crossing profile above. Boreholes and tTEM soundings have been projected onto the profiles using buffer zones of 100 m and 25 m respectively. The buffer for SkyTEM data is 100 m.

7.3.1 Profile SW-NE 1 (Figure 7.4)

This profile runs along a buried valley in the north-western part of the study area. The deep parts of the profile show Danian limestone to the SW and Maastrichtian chalk to the NE. Although most of the pre-Quaternary sediments lie below the DOI, the interpretations are supported by borehole data. Both sediment types show high resistivities (red/purple colours), but lower resistivities (green/blue colours) deep in the Maastrichtian chalk point to occurrence of saline porewater.

According to Klitten & Wittrup (2006), the Danian limestone generally has a higher resistivity than the Maastrichtian chalk, and in the eastern part of Denmark, a sequence of marls in the chalk often constitute the boundary between fresh water above and saline water below. Between 3.100 and 4.300 m on the profile, low-resistive parts of the deep succession with presumably saline porewater have a step-like appearance pointing to differences in the porosity and permeability. Because of this, two faults are tentatively sketched in the deep middle part of the profile. This interpretation is, however, uncertain because of the location below the DOI, and the exact boundary between the Maastrichtian chalk and the Danian limestone is difficult to determine from the tTEM data alone.

The lower resistivities at the top 10-15 m of the Maastrichtian chalk, most clearly seen at the profile distance 6.500 to 7.200 m, points to the presence of clay. This is interpreted as marls, which could be the Rørdal Member (see Section 4.1). The top of the pre-Quaternary succession lies between 20 m b.s.l. and 35 m a.s.l. – deepest to the SW.

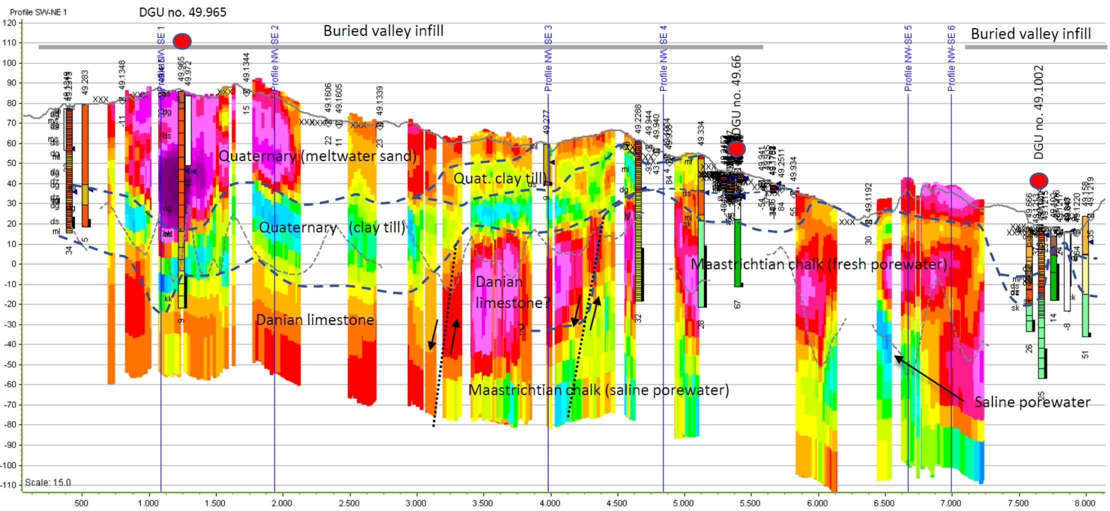

Figure 7.4: Profile SW-NE 1. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

The Quaternary succession is up to a bit more than 100 m thick to the SW but only up to 50 m and occasionally just a few metres thick to the NE. To the SW, the sediments comprise up to 40 m thick clay tills at the bottom and predominantly meltwater sand and a few meters of till above. Apparently, the downfaulting of the pre-Quaternary succession in the southwestern part of the profile has made room for deposition of the Quaternary clay. The Quaternary sediments comprise infill of a NE-SW oriented and completely buried valley. The profile is located along this valley, and between 4.500 and 7.200 m – above the Maastrichtian chalk - the valley bottom becomes very shallow. To the SW, the unsaturated zone is very thick (up to 40 m) resulting in high resistivities, which means that the tills in the upper parts have unusually high resistivities, and therefore distinction between sand and till in the tTEM models is difficult.

7.3.2 Profile SW-NE 2 (Figure 7.5)

The SW-NE profile 2 is located roughly parallel to profile SW-NE 1 and is located on the flank of the buried valley mentioned above. The pre-Quaternary succession shows roughly the same structure as the preceding profile, but the upper surface is not eroded as deep as on the preceding profile. The low resistivities between 5.900 and 6.600 m on the profile are interpreted as Maastrichtian marls. These marls appear to be removed by erosion to the north-east. Saline porewater rises to higher elevations between 6.800 and 7.500 m and this is presumed to be caused by a fault with a location coinciding with the topographic low between 7.300 and 7.500 m.

The thickness of the Quaternary is generally less than on the preceding profile, and the clay and sand layers along the profile have an apparently more complex architecture in the central and southwestern parts. The north-eastern part, however, shows a 10 to 15 m thick layer with slightly lower resistivities than the sediments above. According to boreholes, this is clay till and meltwater clay/sand, and apparently the layer can be found along the profile for around 3 km. As indicated on the profile, much of the Quaternary sediments are representing buried valley infill. But because of minor resistivity contrasts and a complex build, the delineation of the valley infill along the profile is difficult.

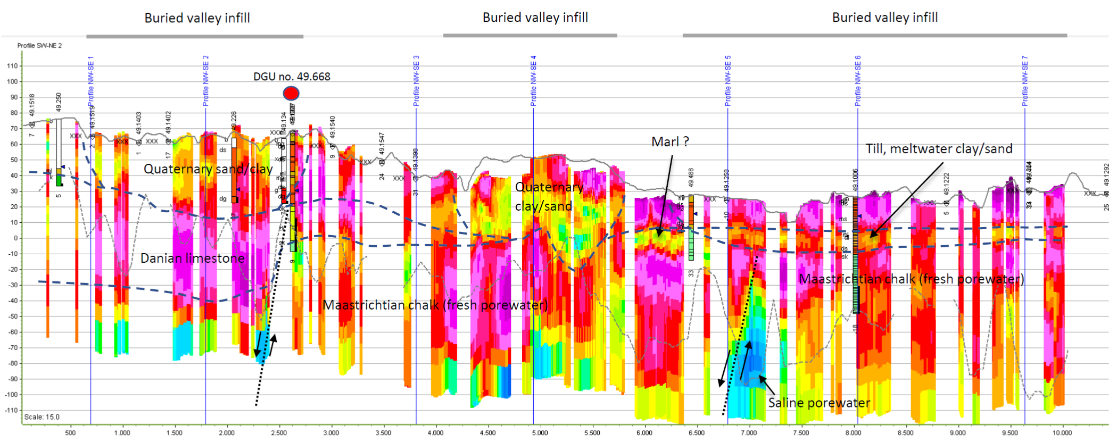

Figure 7.5: Profile SW-NE 2. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.3 Profile SW-NE 3 (Figure 7.6)

Profile SW-NE 3 shows approximately the same picture as SW-NE 2, but the Maastrichtian marls in the top of the chalk are mapped almost throughout the profile, nicely delineating the top of the chalk, both against the Danian limestone to the left and against the Quaternary sediments to the right. The boundary between the Danian and the Maastrichtian has a step-like appearance, and it is assumed – just as for the preceding profiles – that the sediments are offset along a number of faults. This is underlined by the presence of saline porewater in the chalk at high elevations within the chalk (at c. 3.800 m). To the right on the profile, the inferred faults seem to offset the marls at the top of the Maastrichtian and apparently, they also affect the surface topography.

To the north-east, the hilly terrain is characterised by very high resistivities. The hills are composed of Quaternary meltwater sand of which most is unsaturated. This is also the case for the remaining part of the profile, leaving the resistivities of the Quaternary layers high, despite descriptions of clay layers in some boreholes.

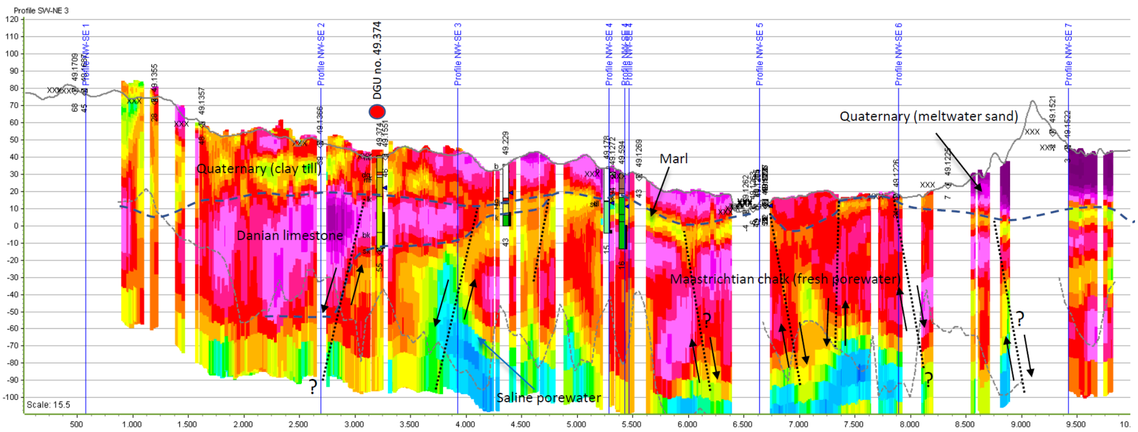

Figure 7.6: Profile SW-NE 3. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.4 Profile SW-NE 4 (Figure 7.7)

The Profile SW-NE 4 has a build much similar to the SW-NE 3 profile. In the north-eastern half of the profile, however, the very high resistivities of the meltwater sediments in the hills reach much deeper than on the preceding profile. The high-resistivity sand appears to lie directly on the Maastrichtian chalk/marls, which here attains a fairly low resistivity. A water sample from a screen placed in the top of the chalk in borehole DGU 49.370 shows fresh porewater, which means that the low resistivities between 20 to 40 m b.s.l most likely represent marl. This, on the other hand, means that the Maastrichtian chalk is not eroded but downfaulted around 30 m or more – presumably along a fault at 6.400 m. In the middle part of the profile, the Maastrichtian chalk is lying at a high elevation, but the marls seem here to be disturbed – either deformed by glaciotectonics or faulted (between 4.600 and 5.700 m).

Between 3.700 and 4.400 m the sounding data on the profile is from a SkyTEM acquisition. Although the resolution is not as good as the tTEM, low resistivities around 10 m a.s.l. presumably represent marls close to the top of the Maastrichtian. Several faults are interpreted to offset the pre-Quaternary succession and facilitate enhanced upward transport of saline groundwater (see the profile at depth between 2.800 and 4.400 m)

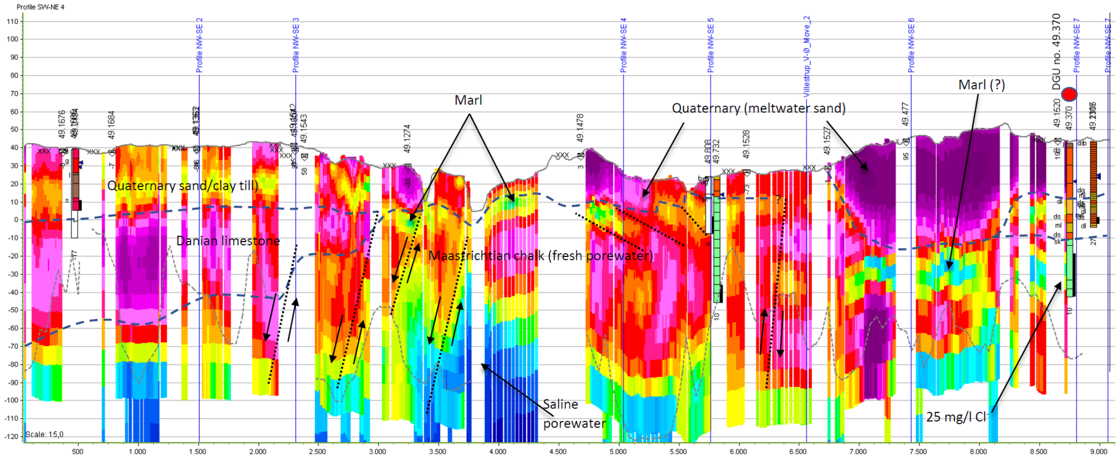

Figure 7.7: Profile SW-NE 4. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location. Between 3.700 and 4.400 m the data visible are SkyTEM.

7.3.5 Profile SW-NE 5 (Figure 7.8)

Again great resemblances between this profile and the preceding: The downfaulted part of the succession to the north-east and a presumed fault around 6.400 m, the marls in the upper part of the Maastrichtian chalk at varying elevations to the south-west, and the downfaulted Danian limestone at the far south-west. The Quaternary succession generally has very high resistivities although consisting of both sand and clay layers.

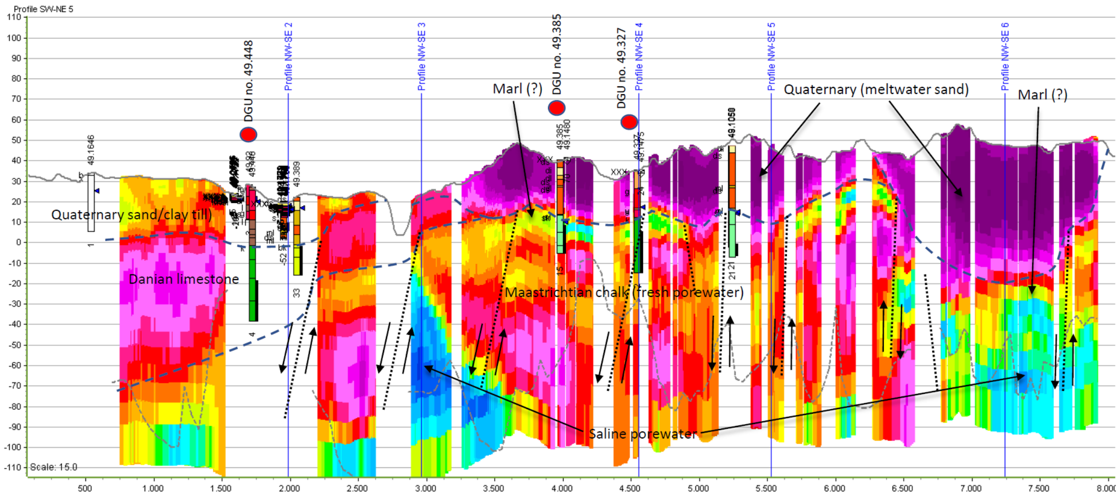

Figure 7.8: Profile SW-NE 5. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.6 Profile NW-SE 1 (Figure 7.9)

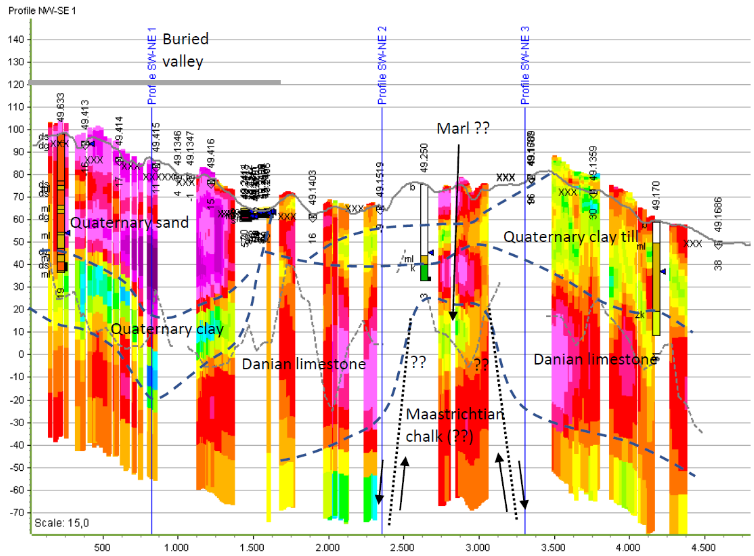

Figure 7.9: Profile NW-SE 1. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

This profile is located to the south-west in the study area and crosses the buried valley shown on the left side of the profile. The Danian limestone is found at high elevations outside the buried valley (up to 40 – 50 m a.s.l.). At the centre of the profile, Maastrichtian chalk is tentatively interpreted to be located at a quite high elevation, because of a local occurrence of low resistivities that might be the Maastrichtian marls. This is, however, based on a very limited amount of data and is therefore quite uncertain. Low resistivities in the Danian limestone at this elevation would be difficult to explain. An alternative explanation for the low resistivities could be a narrow clay-filled Quaternary valley. Further detailed geological interpretations may be able to refine the picture.

The Quaternary succession inside the buried valley is split into a deep clayey part and an upper sandy part. Outside the buried valley the Quaternary is probably dominated by tills, as seen both in borehole data and tTEM.

7.3.7 Profile NW-SE 2 (Figure 7.10)

This profile crosses two buried valleys of which the south-eastern one is dominated by meltwater clay and clay tills. This is confirmed by the generally low tTEM resistivities; intervals with higher resistivities in the uppermost part may be due to a high sand/gravel content of the clays. This valley is mentioned earlier and has previously been mapped with SkyTEM. The north-western valley shows the same infill as on the preceding profile.

The boundary between the Maastrichtian chalk and the Danian limestone undulates which is interpreted based on the resistivity variations. Patches of lower resistivities around 30 to 40 m b.s.l. in the centre of the profile points to presence of marl (see also the interpretations of the previous profile). This, together with the markedly higher resistivities of the limestone above, seems to fit with a faulted pre-Quaternary succession. The valley to the south-east is eroded deeply into the Maastrichtian chalk whereas the north-western valley is shallower and apparently only eroded into the Danian limestone.

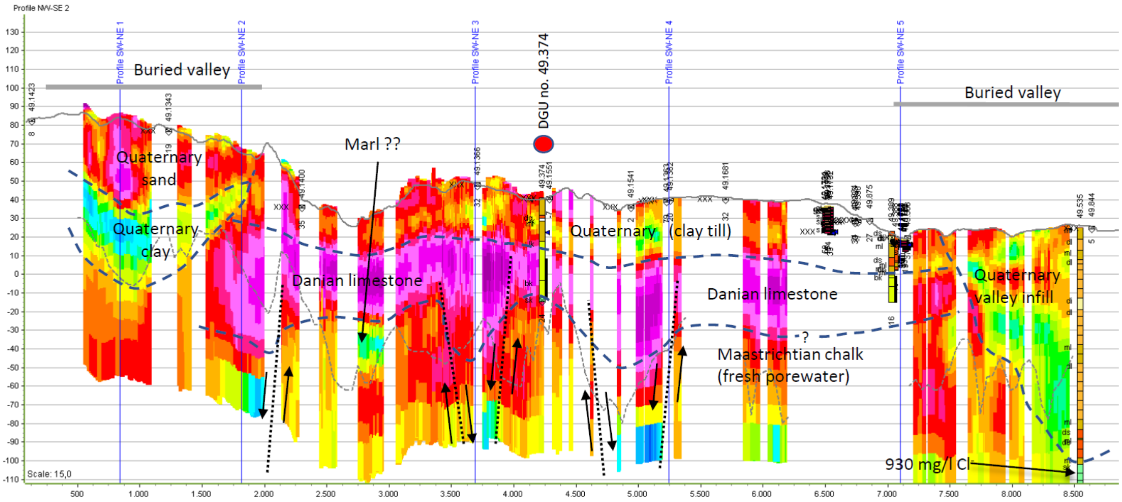

Figure 7.10: Profile NW-SE 2. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.8 Profile NW-SE 3 (Figure 7.11)

The pre-Quaternary succession shows changes in elevation of the Danian/Maastrichtian boundary at the locations 2.000 and 6.700 m pointing to faults offsetting the layers up to 30-50 m. The Maastrichtian chalk shows large patches with very low resistivities pointing to saline porewater, and intervals of slightly lower resistivities in the top pointing to presence of marls. The Danian limestone generally has high resistivities.

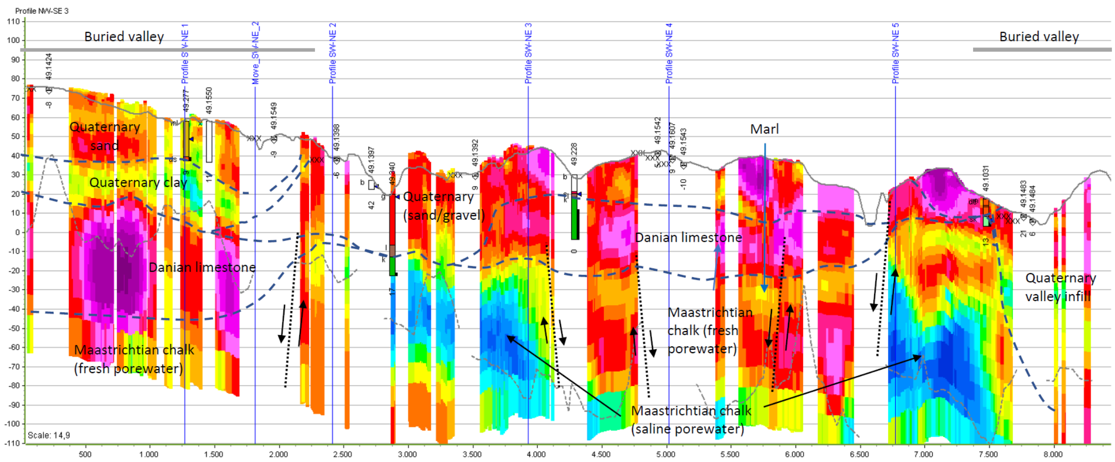

Figure 7.11: Profile NW-SE 3. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.9 Profile NW-SE 4 (Figure 7.12)

On this profile, the Danian limestone is removed by erosion. The top of the Maastrichtian shows the slightly lower resistivities of the marl layer, more or less defining the boundary to the Quaternary. The boundary lies at varying elevations and because the marl is present, this points to faulting rather than erosion. The marl cannot be interpreted from the data to the north-west and therefore erosion may have removed the upper part of the Maastrichtian chalk here. The borehole DGU 49.2288 describes soft chalk, which points to a Maastrichtian age.

The buried valley to the north-west is here quite narrow compared to the preceding profiles. On the NW-SE 4 profile, the valley is eroded into Maastrichtian chalk, whereas on the preceding profiles, it was eroded into the Danian limestone. This hints at a difference in the erodibility of the two types of pre-Quaternary sediments. The buried valley to the south-east is not covered by tTEM data, but the valley interpretation based on the previous SkyTEM mapping is sketched on the profile. The Quaternary succession outside the valleys is sandy and clayey, and the tTEM does not allow for detailed delineation of individual layers.

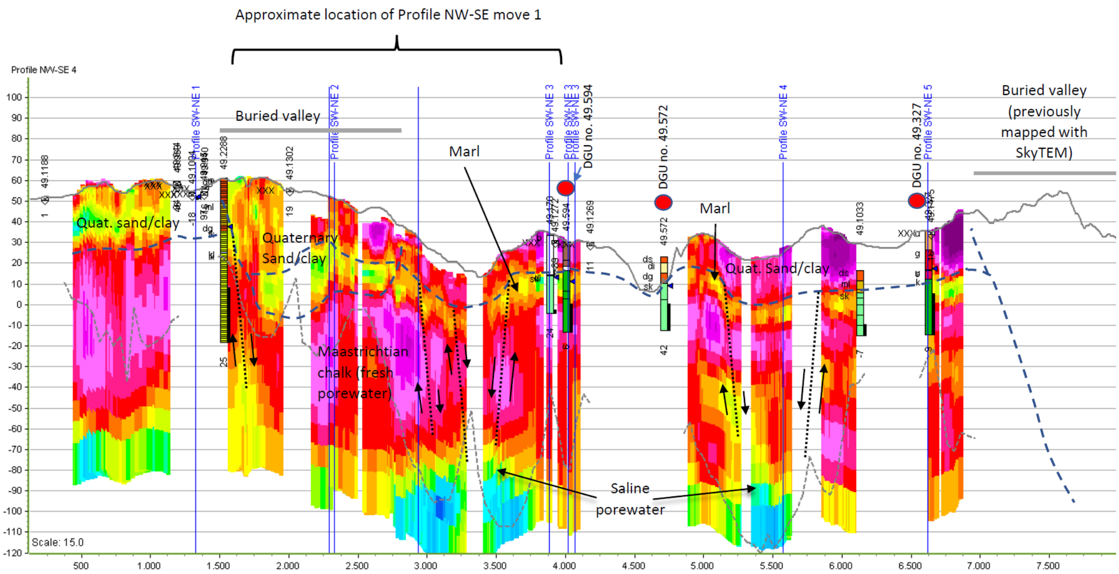

Figure 7.12: Profile NW-SE 4. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.10 Profile NW-SE 5 (Figure 7.13)

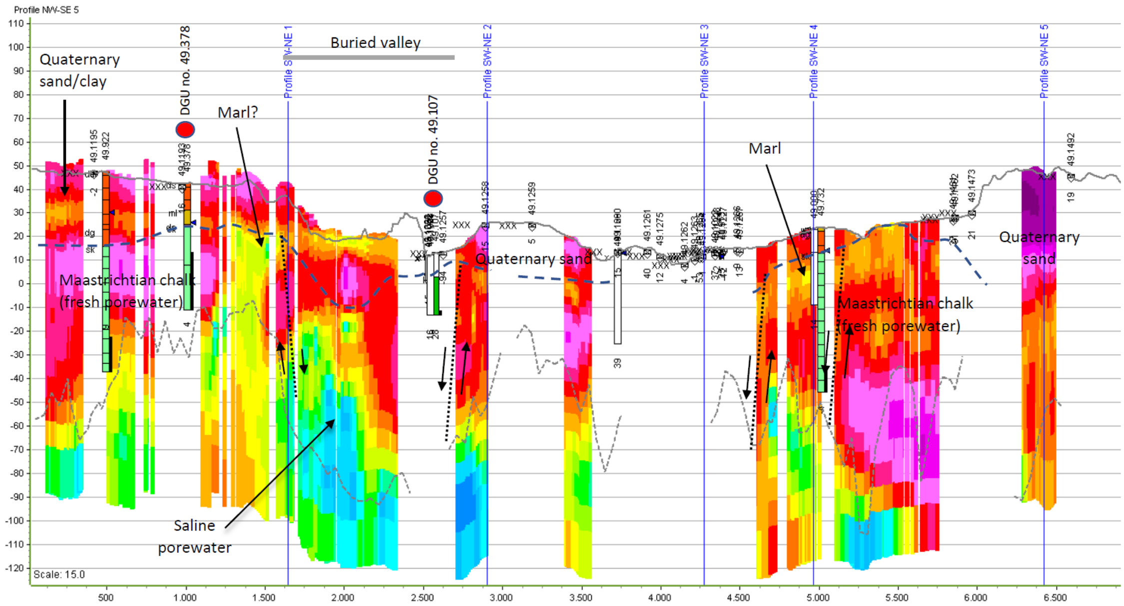

Figure 7.13: Profile NW-SE 5. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

The pre-Quaternary sediments are Maastrichtian chalk only. The upper boundary of this is defined by the slightly lower resistivities of the marls, but between 0 and 1200 m, and between 1.700 and 2.300 m, the marl seems to be eroded away. However, between 1.700 and 2.300 m the interpretation is rather uncertain; the low resistivities between 10 and 20 m b.s.l. could be downfaulted marls, and the low resistivities underneath is probably represent saline porewater.

The buried valley is apparently narrow here and the bottom of the valley is tentatively chosen right above the low resistivities. This interpretation is uncertain because there is no confirmation in boreholes. The Quaternary succession is predominantly sandy.

7.3.11 Profile NW-SE 6 (Figure 7.14)

The Maastrichtian chalk shows large patches of saline porewater in the south-eastern part of the profile, and the upper surface of the chalk appears to be undulating. The Rørdal Member marls appears to be present to the north-west and to the south-east, but not in the central parts of the profile.

The buried valley is tentatively interpreted to be present between 0 and 4.000 m on the profile, and in contrast to the south-western parts of the valley (see Figure 7.4), a sand layer can here be found in the deepest parts of the valley.

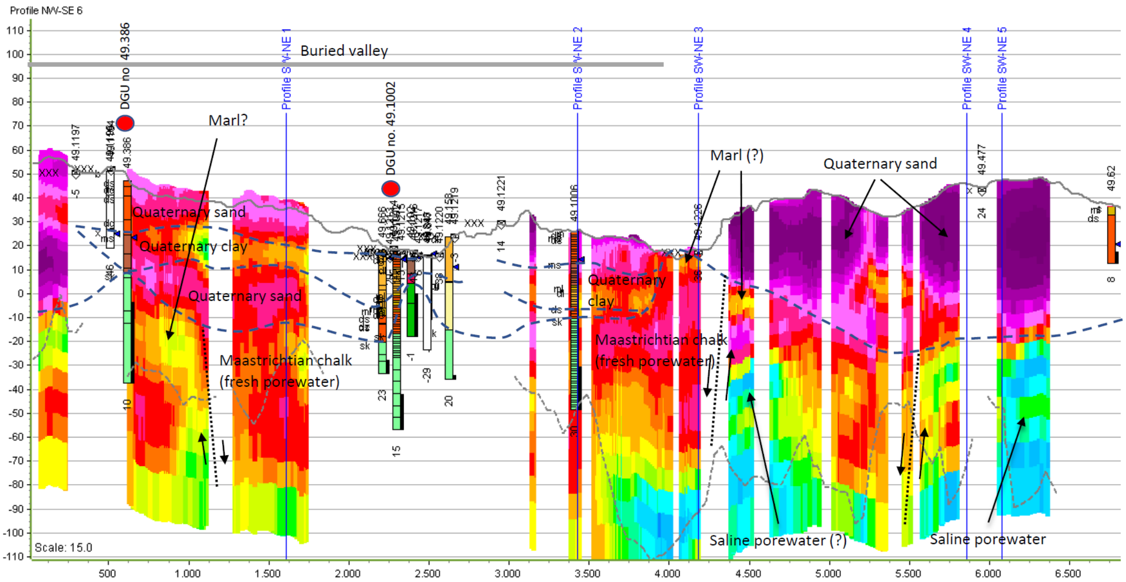

Figure 7.14: Profile NW-SE 6. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.12 Profile NW-SE 7 (Figure 7.15)

This profile is located inside the buried valley meaning that all of the Quaternary sediments represents valley infill. The Quaternary succession has a very high resemblance with the valley infill on the other profiles. Most of the sediments are unsaturated and the resistivities are generally very high.

The lower to slightly lower resistivities seen at the top of the Maastrichtian chalk are presumably caused by the presence of marl.

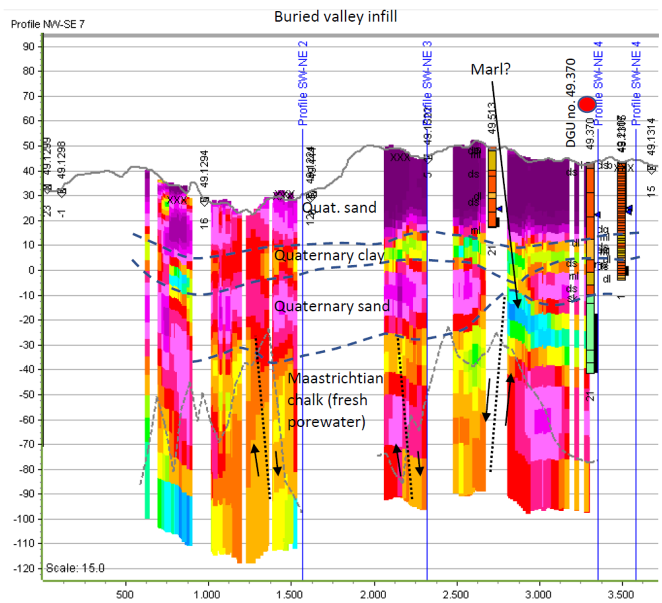

Figure 7.15: Profile NW-SE 7. Depth of investigation (DOI) is shown with hatched grey line. Vertical exaggeration: 15x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

7.3.13 Profile NW-SE move 1 (Figure 7.16)

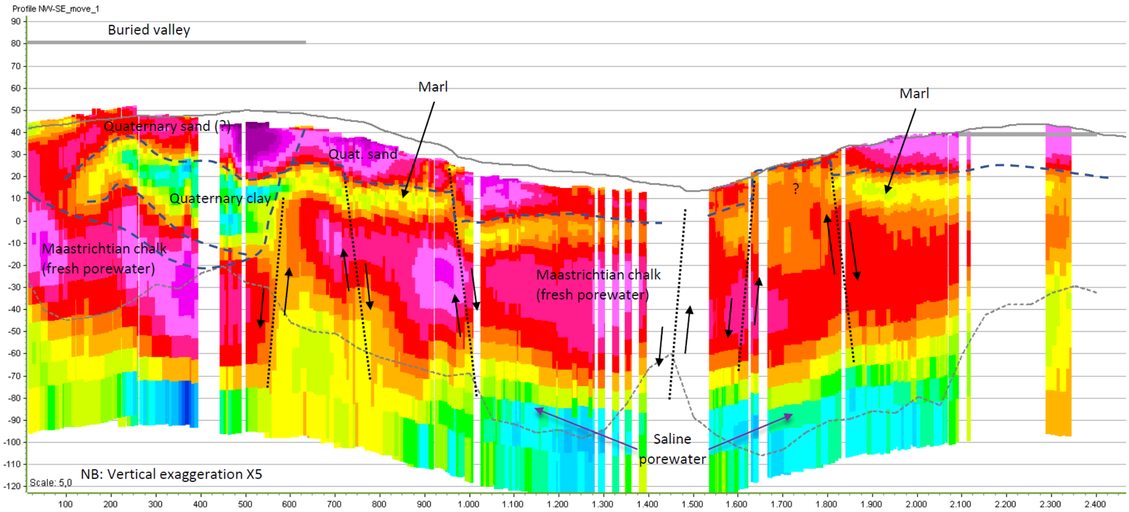

Figure 7.16: Profile NW-SE move 1. Depth of investigation (DOI) is shown with hatched grey line. NB: Vertical exaggeration: 5x. See Figure 7.2 for resistivity legend and Figure 7.1 for location.

This is a short profile with a three times smaller vertical exaggeration than the other profiles. The profile location is shown on Figure 7.1, and it lies close to the north-western part of Profile NW-SE 4 (Figure 7.12). The profile illustrates the detail, that can be attained when looking at the data at other scales.

What is clearly seen is the shifting levels of the low-resistivity layer interpreted as marls close to the top of the Maastrichtian chalk. Tentative interpretations of faults highlight the possible cause for the offset of the marl. The valley infill of the buried valley is also nicely outlined - despite that the bottom of the valley is uncertain. The marls are apparently missing here because of the valley erosion, and therefore the top of the Maastrichtian here cannot be mapped based on the resistivities alone.

7.4 Conceptual geological model

The overall conceptual model of the study area is illustrated in the profile sketch in Figure 7.17 and on the map in Figure 7.18.

7.4.1 The pre-Quaternary succession

- The oldest part of the pre-Quaternary succession consists of the Upper Cretaceous chalk (Maastrichtian). The chalk is generally white to greyish white, soft, and with some flint. In the upper part, a sequence of marl layers (presumably the Rørdal Member; see Figure 7.17) constitutes a widespread marker horizon that shows lower resistivities than the rest of the chalk. This horizon is in many places mapped by tTEM. This will extend the area where marls in the upper part of the Maastrichtian chalk can be found further to the south than described by Nielsen & Jørgensen (2008).

- The youngest pre-Quaternary sediment is the Danian limestone which generally is greyish white, hard to very hard, and typically containing much flint. The Danian limestone appears to have a higher resistivity signature than the chalk below.
- The Danian limestone is removed by erosion in the north-eastern half of the study area (Figure 7.18), and it appears that where present, the Danian limestone is downfaulted along NW-SE faults and have thus been protected from erosion.
- Faults are frequently occurring in the study area and in some areas correlations between the topography and interpreted faults have been found. This is especially exemplified by the profile in Figure 7.16, where there is a resemblance between the topography and the undulating top of the faulted Maastrichtian chalk below. This could indicate fault activity during the Quaternary.
- Deep saline porewater is seen as low resistivities in the Maastrichtian chalk at depth - occasionally rising to higher levels in the subsurface, especially under topographic lows and along faults. Caution should be applied when interpreting the lithology of the deep parts of the succession because of limited resolution and because of presence of saline porewater. On the other hand, resistivity variations at depth caused by saline porewater can help the interpretation of structures, and in some cases also hint at porosity and permeability variations.
- Palaeogene clays that are present further to the west have not been found within the study area.

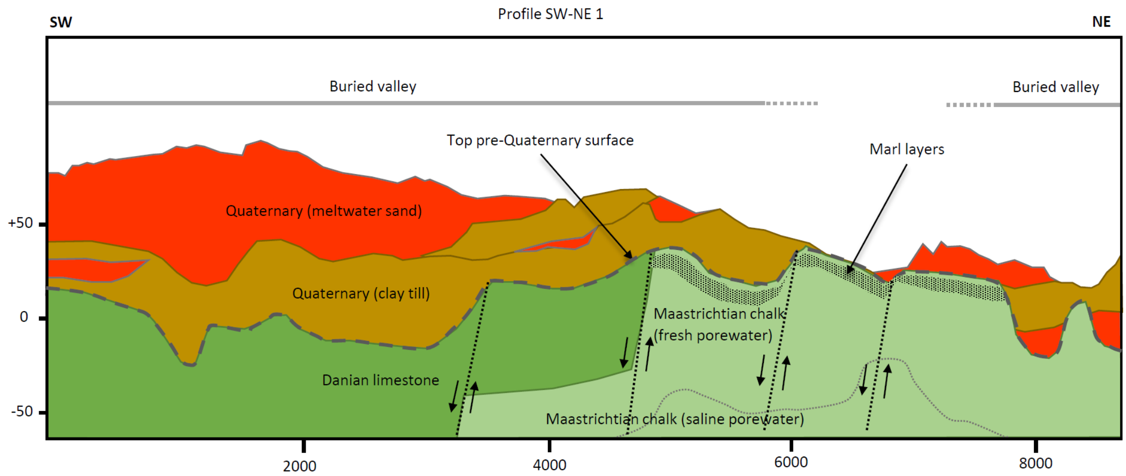

Figure 7.17: Profile SW-NE 1 sketch. For location, see Figure 2.7 and Figure 7.18. Vertical exaggeration: 15x. The southwestern part of the profile runs along a Quaternary buried valley, where the infill is thick.

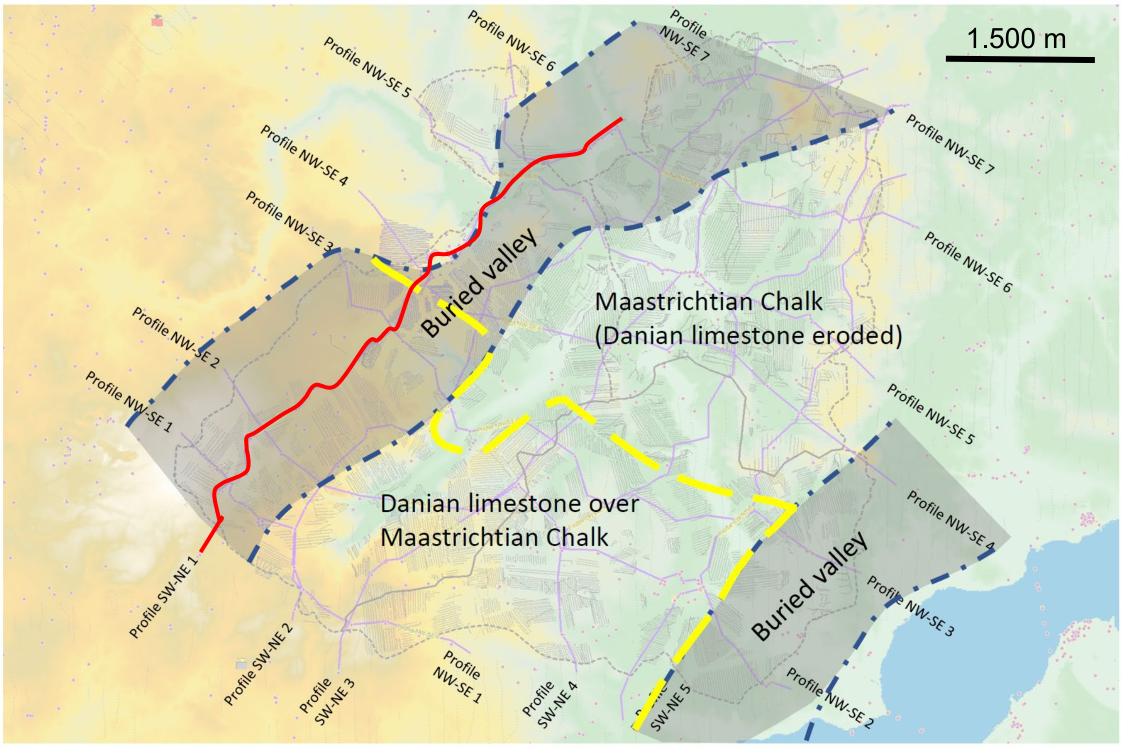

Figure 7.18: Tentative geological interpretation based on the geological profiles. See text for explanation. The red line marks the location of the profile in Figure 7.17.

7.4.2 The Quaternary succession

- The Quaternary sediments rest directly on the Danian limestone towards southwest and on the Upper Cretaceous Maastrichtian chalk to the north-east.
- The Quaternary succession is dominated by two southwest – northeast oriented buried valleys. The valleys are between 1.5 and 2.5 km wide and in some places more than 100 m deep. A narrow valley under a topographic valley perpendicular to the large valleys has earlier on been mapped with SkyTEM (Sandersen & Jørgensen, 2016), but this valley has not been confirmed by the tTEM-data because of poor coverage in this area.
- The south-eastern valley is eroded through the Danian limestone and down into the Maastrichtian chalk and has a clay-dominated Quaternary infill. The north-western valley is eroded into the Danian limestone in the southwestern part and into the Maastrichtian chalk to the northeast. The valley has both sandy and clayey infill, but a consistent and seemingly undeformed layering seems to be present.
- The large buried valleys and the tunnel valleys in the topography (Figure 2.1) roughly share the same orientations.
- The buried valleys are interpreted as tunnel valleys formed beneath the Pleistocene ice sheets, and the NE-SW orientation matches the orientation of the Main advance 23-21.000 years ago (Figure 4.2B). This is, however, just a tentative interpretation because the valleys show orientations perpendicular to the Sorgenfrei-Tornquist Zone and therefore the valley erosion could have been influenced by the presence of faults and depressions along fault zones. If so, the orientation of the valleys cannot

be related to specific ice advances and cannot be used as an age indicator (cf. Sandersen & Jørgensen 2022)

- The Quaternary succession outside the buried valleys is dominated by high resistive sediments, mostly meltwater sand and gravel. However, tills are found in several boreholes, and the high resistivities of the tills can therefore be due to a high sand/gravel content, a high calcium content, or a thick unsaturated zone.
- Lateral correlations within the Quaternary succession outside the buried valleys are difficult.

7.4.3 The influence from faults on erosion, groundwater flow, and vulnerability

It is obvious from the preceding description of the vertical profiles that faults are common. The profiles in Figure 7.4 to Figure 7.15 show that the Danian limestone and the Maastrichtian chalk are located at varying elevations, for example on Profile SW-NE 1 (Figure 7.4) at 4.300 m, where there appears to be an offset of 30-40 m between the Danian limestone and the Maastrichtian chalk. Around Aalborg, north of the study area, mapping of the Rørdal Member shows that the marls have been faulted and consequently found at varying elevations in the area (Nielsen & Jørgensen 2008).

On the profile in Figure 7.16, which is shown in a more detailed version than the other profiles, it is clearly seen that the low resistivity marls in the upper parts of the Maastrichtian chalk are offset in several places. An apparent correlation between the elevation of the marl and the topography signals that either the Quaternary erosion/sedimentation is influenced by the pre-Quaternary topography or that the faults have been active during the Quaternary - or both (see Sandersen & Jørgensen, 2022).

For the Danish chalk and limestone aquifers in general, Kidmose et al. (2022) conclude that groundwater flow take place in an inter-connected fracture-matrix system where the porosity in the matrix contain the largest part of the groundwater, while the flow is via the fractures resulting in a high hydraulic conductivity. It can therefore be assumed that the faults and fractures in the study area have a large impact on the present-day groundwater flow. Therefore, in areas where the pre-Quaternary sediments are offset by faults like the situation shown on Figure 7.16 (e.g. at 1.000 m), corridors for fast groundwater flow along fault planes are likely to have been created. This is in places highlighted by local occurrences of saline porewater at high elevations in the subsurface.

The Maastrichtian marls are considered to have an influence on the vulnerability of the aquifers in the chalk. If not faulted, the marl separates aquifers within the chalk, (Nielsen & Jørgensen 2008), and in areas where the uppermost parts of the Maastrichtian chalk have been eroded, the marl layers may also have been removed by erosion. This will most likely influence the vulnerability of the groundwater in the chalk compared to locations where the marls are intact.

7.5 Uncertainties related to the conceptual geological model

The conceptual model described above is intended for use as a basis for 3D geological modelling and groundwater modelling. The data has not been subject to detailed interpretations, and therefore the conceptual model presented has uncertainties that should be evaluated and tested by more thorough inspection of both existing and new data from planned fieldwork.

Because of the general scarcity of resistivity contrasts in the tTEM models, the delineation of especially the boundary between the Maastrichtian chalk and the Danian limestone is in many cases uncertain. The marl close to the top of the Maastrichtian chalk appears to be an excellent marker, but the rather small resistivity contrasts between the marl and the chalk combined with the limited thickness of the marl interval tends to make mapping of the horizon with tTEM challenging at deeper levels in the subsurface. In addition to this, it still remains to be verified that the low-resistive horizon actually represents marls that can be referred to the Rørdal Member. In Surlyk et al. (2010) and Schovsbo et al. (2008), the Rørdal Member is actually found deeper below the Maastrichtian/Danian boundary than seen in the Villestrup area.

Well logging data would be highly valuable for identifying the marls, but unfortunately no logs are available in the study area. For the Danian limestone and the upper parts of the Maastrichtian chalk the distinction between the chalk and the Quaternary sediments based on resistivities can be very difficult – especially if the Quaternary sediments are sandy and thus show high resistivities. Generally, the tTEM data indicate that the Danian limestone has a higher resistivity level compared to the Maastrichtian chalk, and therefore these resistivity differences interpreted together with borehole data have been used to map the boundary between the sediments. This distinction is, however, very uncertain in areas where there is no support from borehole information.

Added to the above are difficulties concerning identification of the type of the pre-Quaternary sediments from borehole information. Usually, the Danian limestone is hard and the Maastrichtian chalk is soft, but apparently in some boreholes the opposite can be found. If the drill samples are of low quality and/or descriptions of the drill samples are as well, uncertainties about the stratigraphy may be high. Closer scrutiny of borehole information and maybe renewed descriptions of older drill samples may lower the uncertainty. New borehole data, however, would be the best way to add new knowledge and to lower the uncertainty.

The sedimentary succession in the study area is highly influenced by faults and erosion, and the conceptual geological model presented in this report does not convey a full picture of neither the faults nor the erosion. As shown on the profiles – especially on Figure 7.16 - faults can be identified if there is a sufficient resistivity contrast and if offsets of well-known layers or horizons are found. A more detailed delineation of the faults in the study area would be beneficial in order to fully understand the structural build and the spatial distribution of the sediments. A topographical analysis combined with a more detailed interpretation of the tTEM models focusing on delineation of faults is therefore recommended, and to that end it appears that the marl layers will be a very useful marker horizon.

8. Geological elements aimed at 3D geological and geochemical modelling

'Geological Elements' (GE) are defined as separate volumes of the subsurface representing groups of layers that can be related to specific parts of the geological history of an area, thus having separate formation histories (Sandersen et al., 2022). Using the GE approach, focus is on sub-dividing the subsurface into larger, discrete lithological volumes that can be related to distinct parts of the geological history. The understanding of the origin of the GEs makes it possible to construct models that divide the subsurface into a limited number of geologically unique volumes that are separated both physically and chronologically in terms of formation.

In relation to further geological modelling, the delineation into separate GEs have the advantage that it is only necessary to model the upper and the lower boundaries of a GE consisting of multiple individual layers. In addition to the GE boundaries, the geological and geophysical data provide details on the lithological variations within each GE.

The interpretations described in the preceding leads to the following suggestion of a GE subdivision of the geological succession in the Villestrup area. The delineated elements are sketched in Figure 8.1 and Figure 8.2 and comprise the following:

- **GE1: The Maastrichtian chalk**.
- **GE2: The Danian limestone.**
- **GE3: Paleogene clays.** Paleogene clays have not been identified within the study area, but the sediments are present just to the west and because future modelling may include these clays, the GE has been included here.
- **GE4: Quaternary sand and clay outside buried valleys.** An upper sedimentary sequence consisting of primarily meltwater sand and gravel and secondarily of (sandy) tills.
- **GE5: Buried valley infill.** A Quaternary sequence consisting of infill of the incised buried valleys. The infill sediments comprise clay and sand.

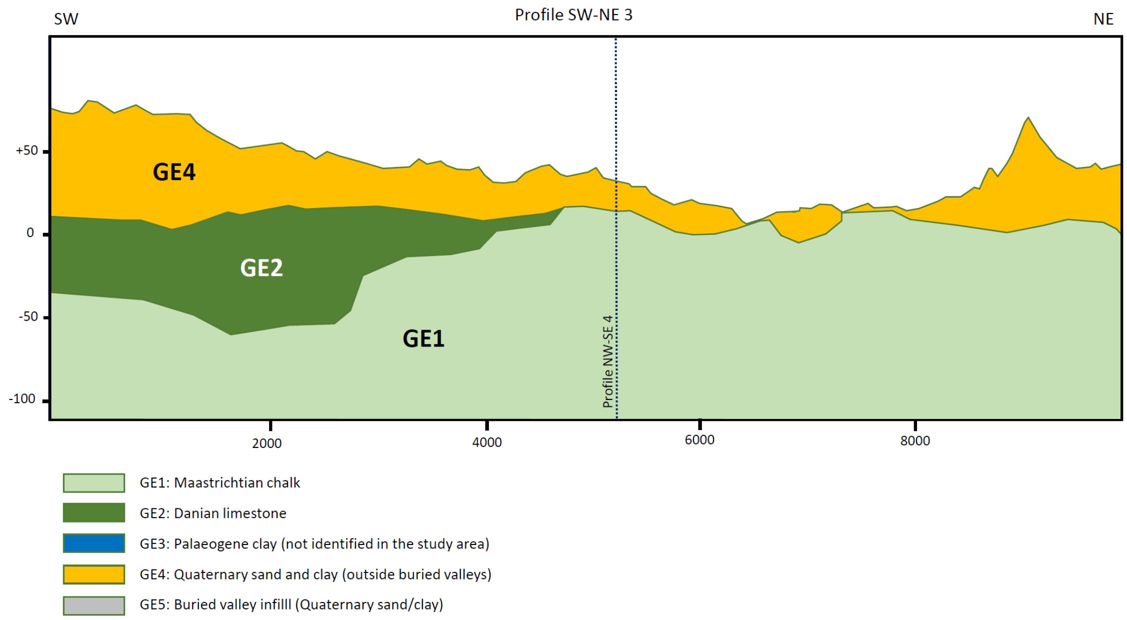

Figure 8.1: Sketch of Geological Elements in the Villestrup area based on Profile SW-NE 3.

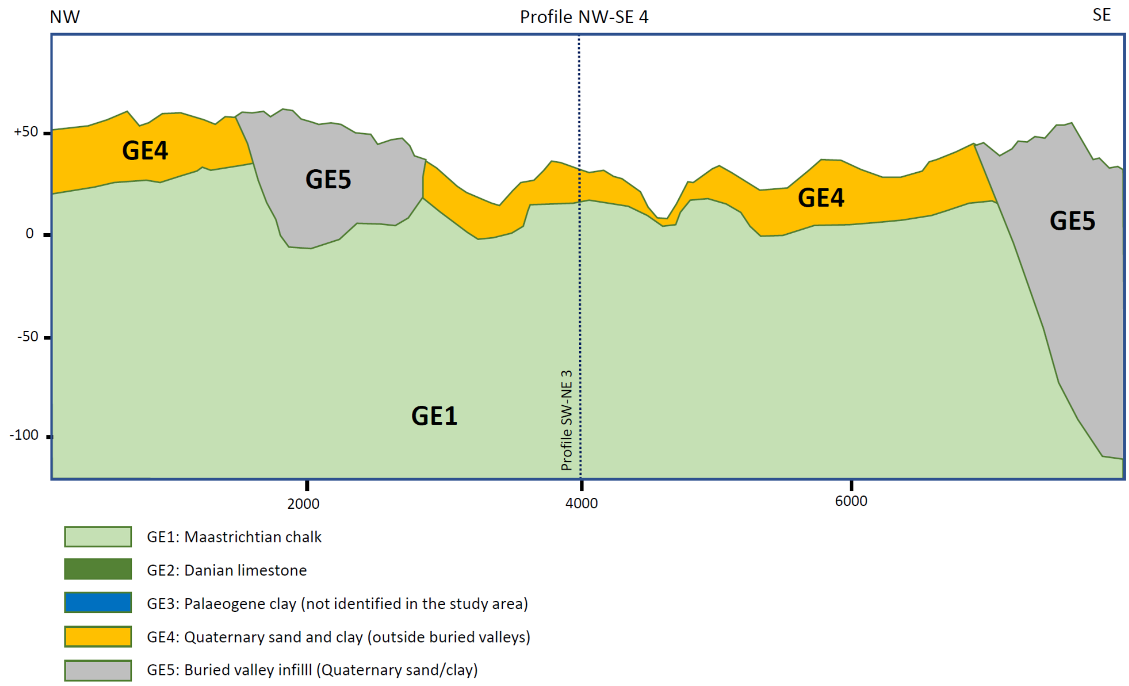

Figure 8.2: Sketch of Geological Elements in the Villestrup area based on Profile NW-SE 4.

9. Summary and conclusions

- **Geophysical mapping:** The area has a good coverage with tTEM data. The tTEM data has a high quality and has significantly added to the understanding of the geological setting. The tTEM resolves a low resistive layer in the top of the Maastrichtian chalk, and this is tentatively interpreted as the marls of the 'Rørdal Member'. At deeper levels, mapping of the marls become more uncertain. The upper parts of the Quaternary succession are sandy and unsaturated, and therefore generally have very high resistivities. This makes distinction between sand and clay difficult.

- **Borehole information:** There is a good coverage with boreholes penetrating into the pre-Quaternary succession. However, the level of information in the soil sample descriptions of the pre-Quaternary layers is generally low and there are no supporting geophysical logs in the boreholes within the study area.

- **Buried valleys:** Two NE-SW oriented buried valleys are mapped within the area. The valleys are up to 100 m deep and are eroded into the pre-Quaternary succession. The buried valleys have orientations that match the topographic valleys in and around the study area.

- **Sedimentary succession:** The study area shows pre-Quaternary chalk and limestone, which is heavily faulted. Danian limestone is downfaulted to the south-west and eroded to the north-east, making the pre-Quaternary surface comprise Danian limestone to the south-west and Maastrichtian chalk to the north-east. The Quaternary succession above consists of tills, meltwater sands and clays, and local occurrences of postglacial freshwater deposits. The Quaternary succession inside the valleys is generally clayey, whereas outside the valleys the sediments are generally sandy.

- **Glaciotectonic deformations:** The topography of the surrounding areas shows pronounced ice-marginal hills, so glaciotectonic deformations in at least the hilly parts is expected. The lack of laterally coherent layers outside the buried valleys points in this direction, but correlations of individual layers is difficult because of small resistivity contrasts. Within one of the valleys there are signs of deformations.

- **Other tectonic deformation:** There are many signs of tectonic events another than glaciotectonics. The study area is located within the Sorgenfrei-Tornquist Zone which is a highly tectonically active area. Several faults have been interpreted within the pre-Quaternary succession and it is likely that also the Quaternary sedimentary succession may be affected by faulting. This type of deformation of the sedimentary succession should be taken into consideration alongside the glaciotectonic deformations when assessing groundwater vulnerability.

- **Geological interpretation and correlation:** Despite a complex setting of the pre-Quaternary succession, a general, preliminary interpretation of the geology has been possible. However, the interpretations are not detailed and has been performed only to provide a conceptual geological understanding of the study area. Further details can without doubt be drawn from the data, and therefore to gain the full benefit of the tTEM data, a more detailed interpretation of the geology is recommended.

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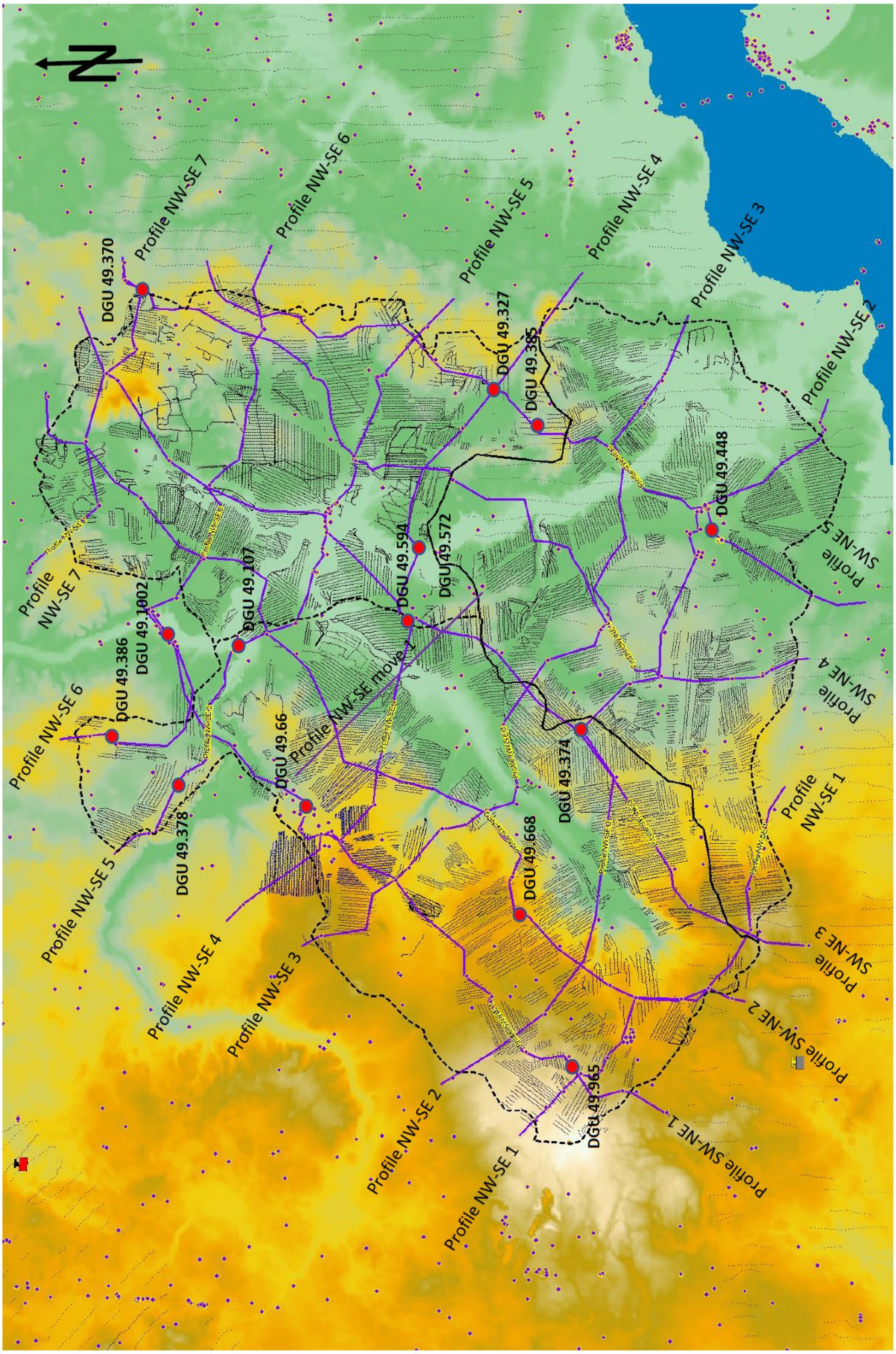
Appendix 1: All geological profiles in larger versions



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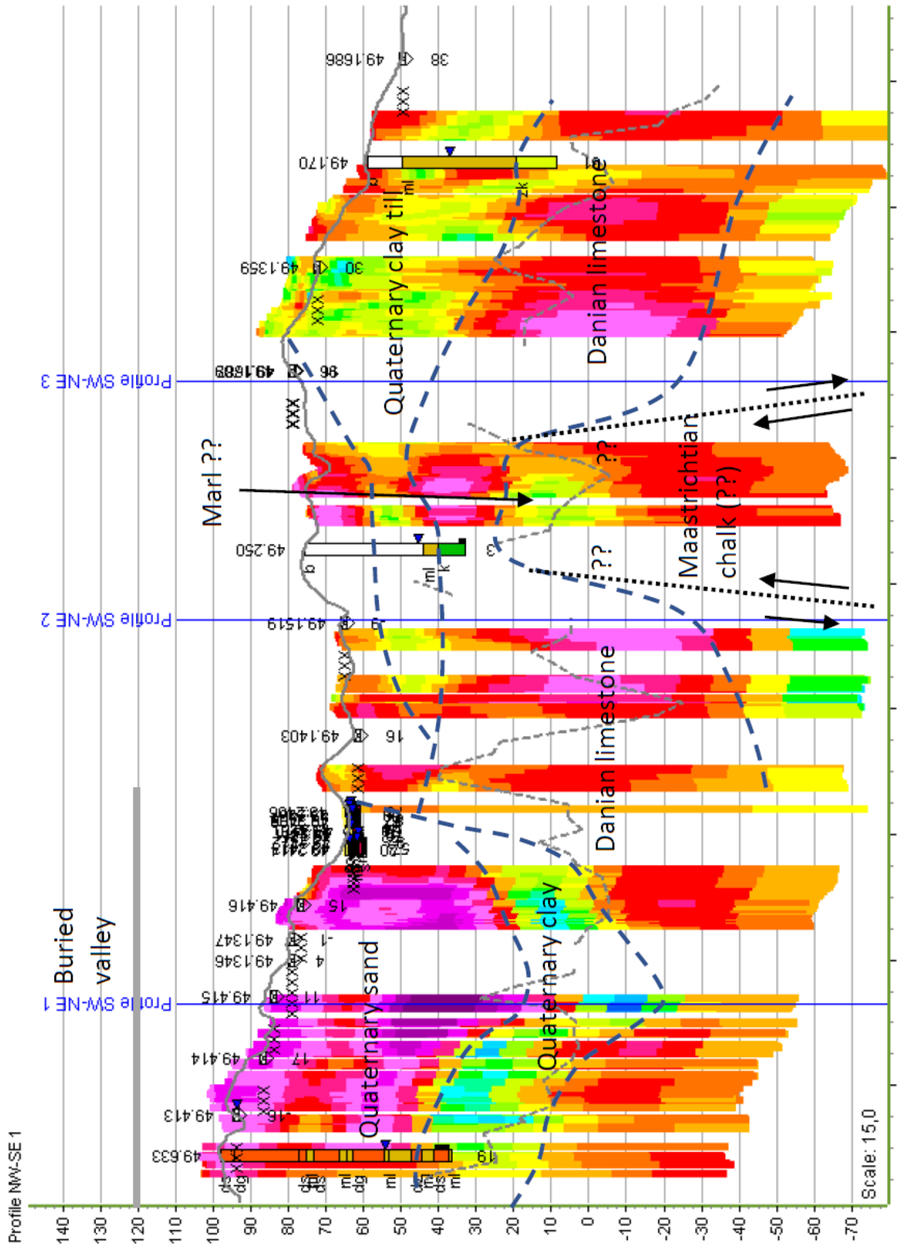
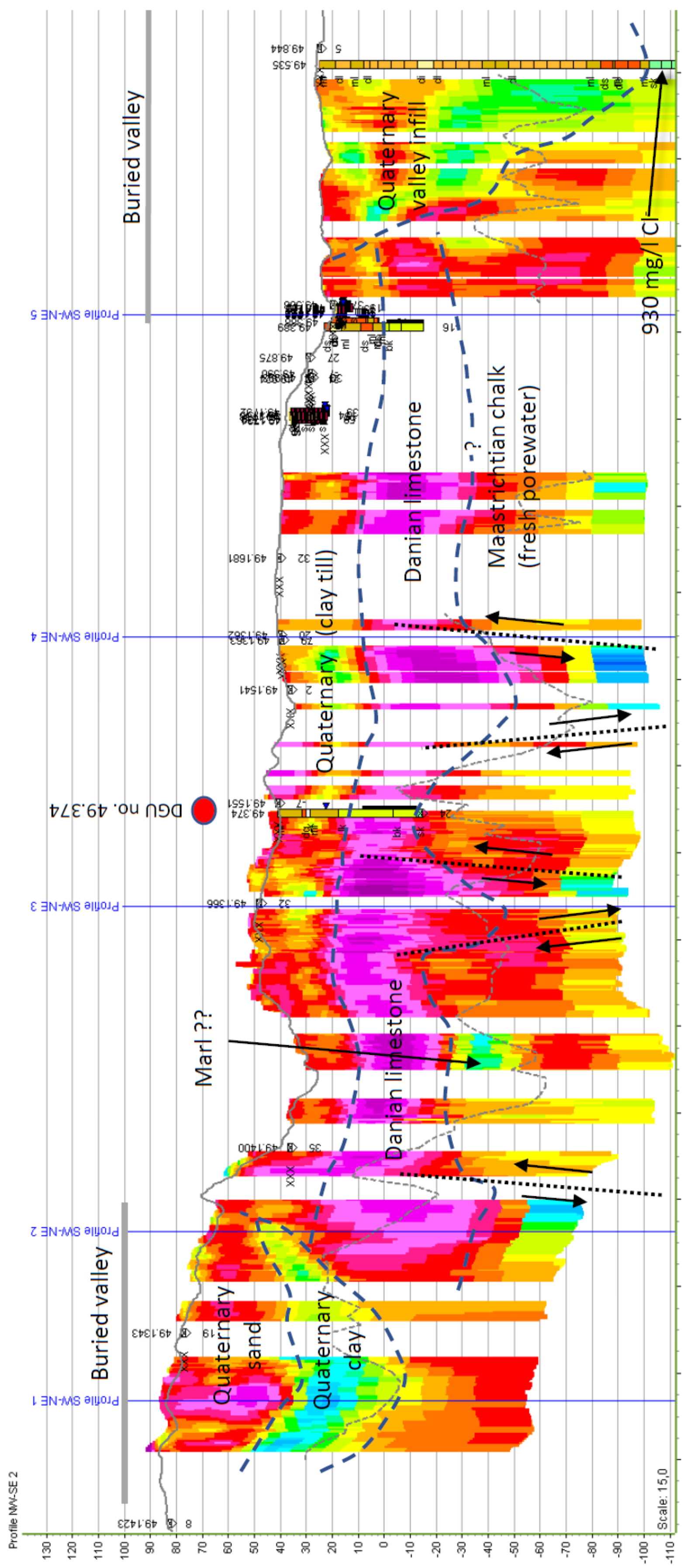
Profile NW-SE 7
Profile NW-SE 6
Profile NW-SE 5
Profile NW-SE 4
Profile NW-SE 3
Profile NW-SE 2
Profile NW-SE 1
Profile NW-SE move 1
Profile SW-NE 1
Profile SW-NE 2
Profile SW-NE 3
Profile SW-NE 4
Profile SW-NE 5
DGU 49.370
DGU 49.327
DGU 49.385
DGU 49.448
DGU 49.594
DGU 49.572
DGU 49.107
DGU 49.1002
DGU 49.386
DGU 49.378
DGU 49.66
DGU 49.668
DGU 49.374
DGU 49.965

Profile NW-SE1



Profile NW-SE 2



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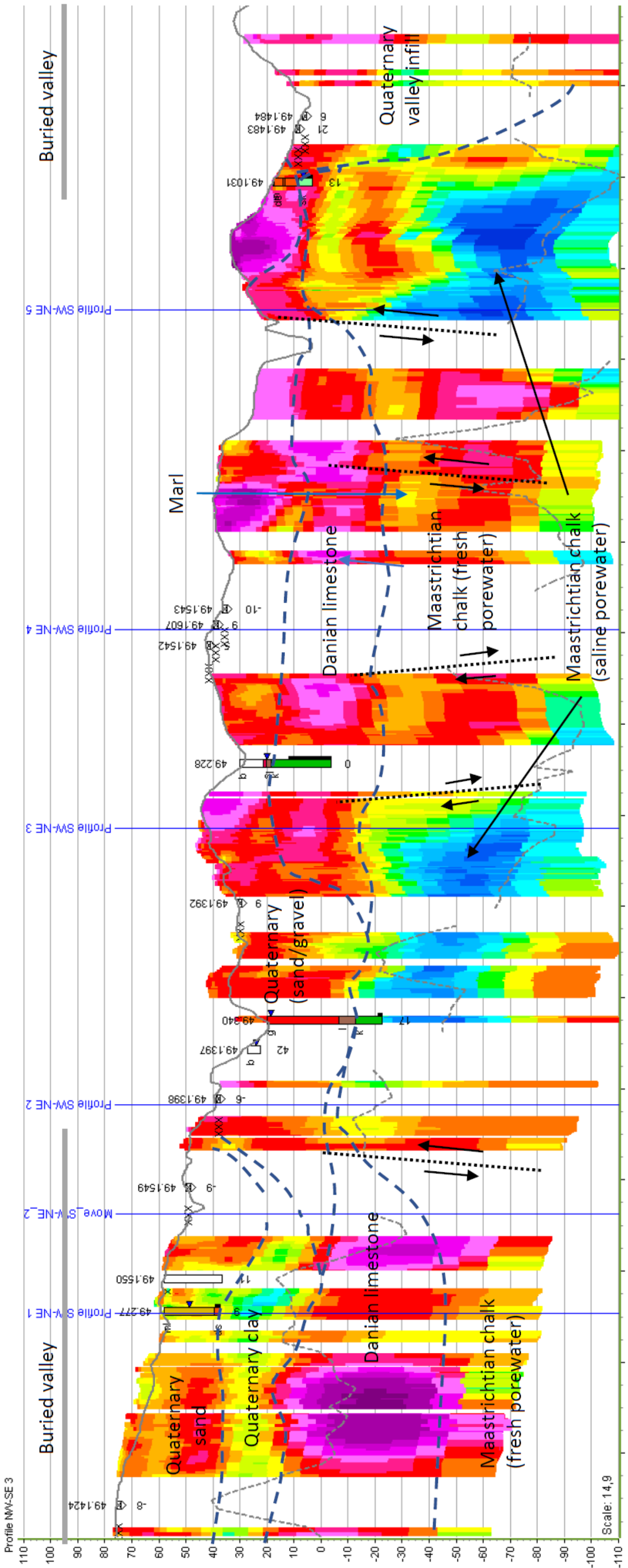

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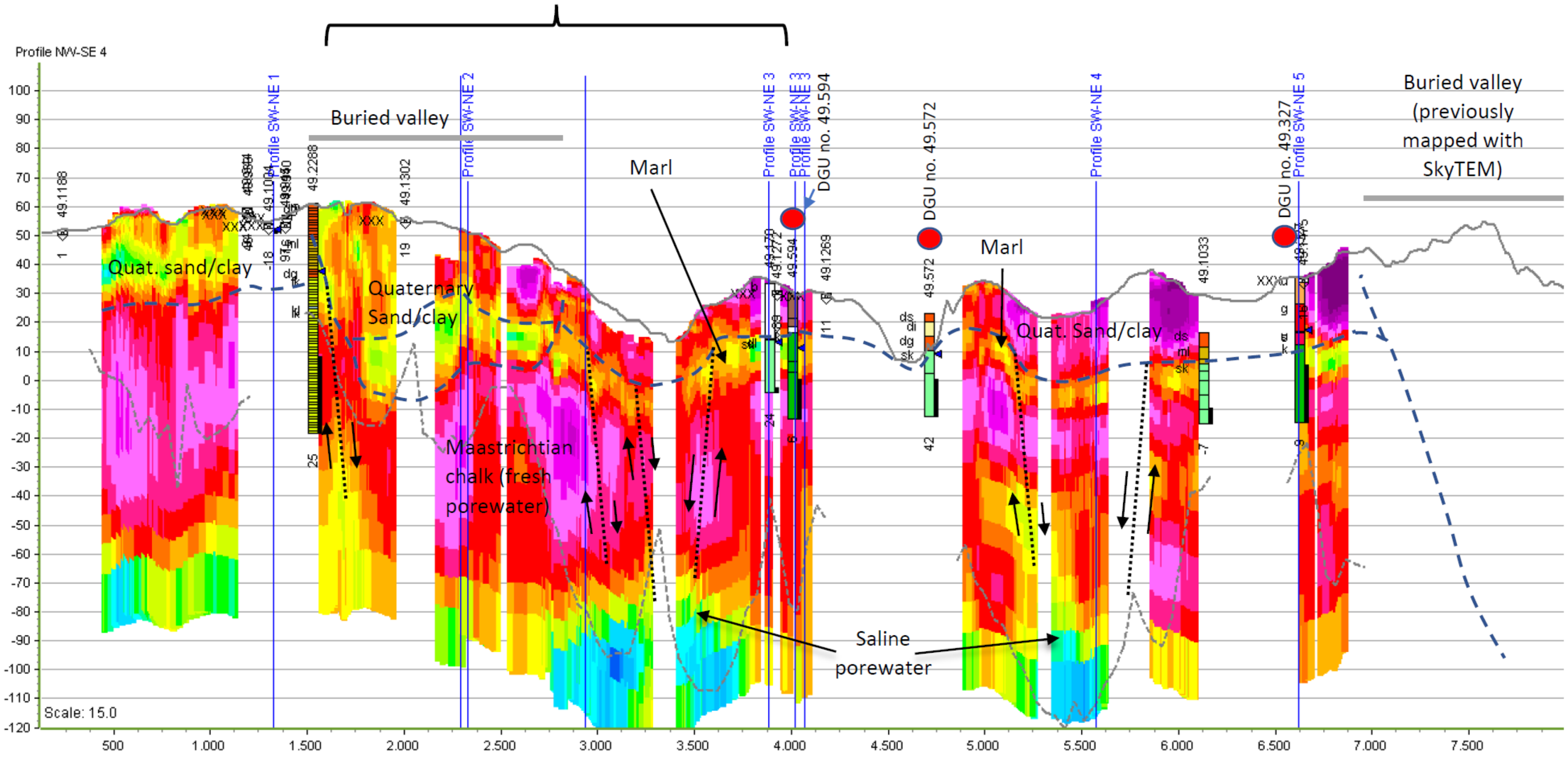

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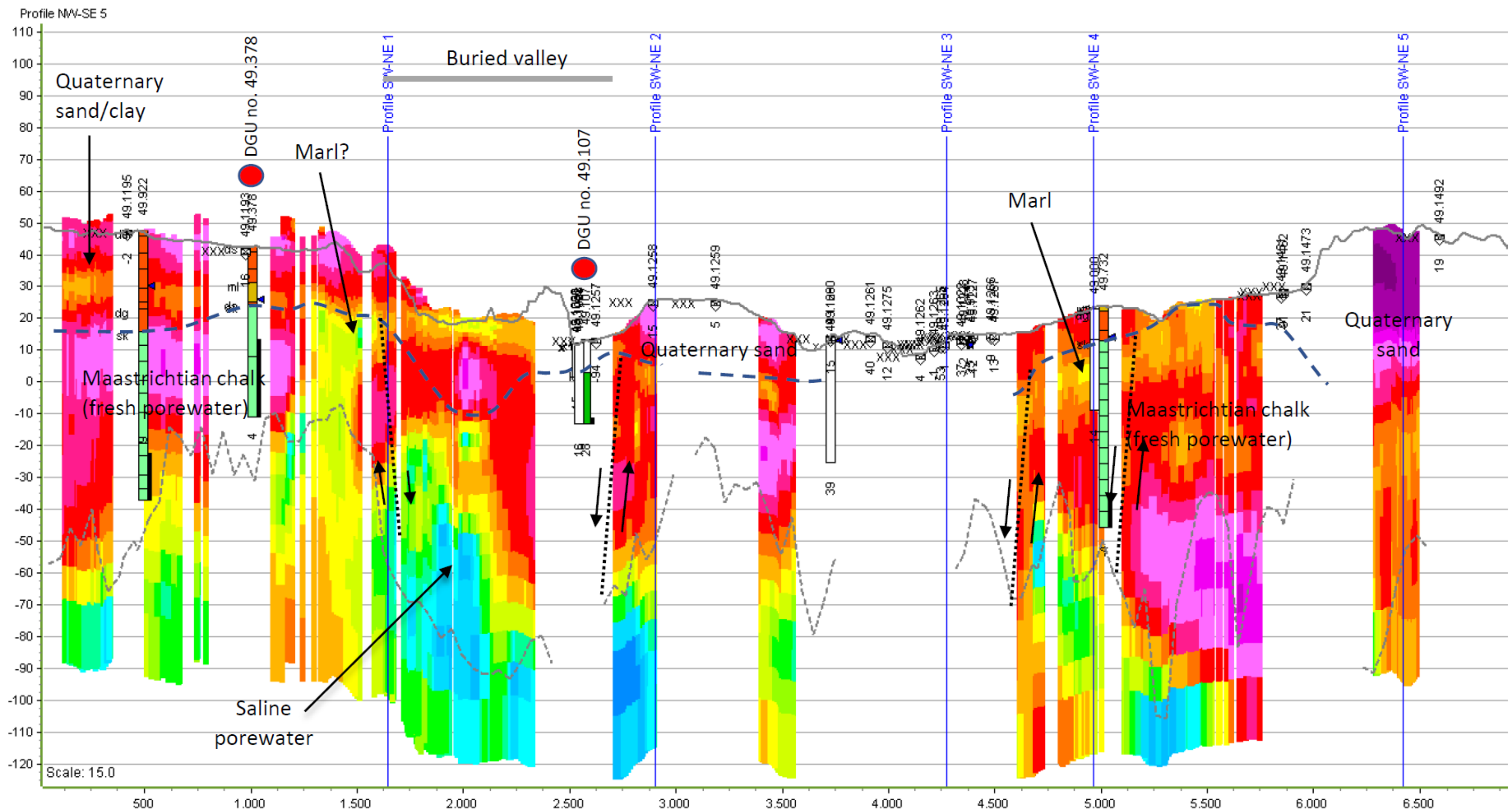

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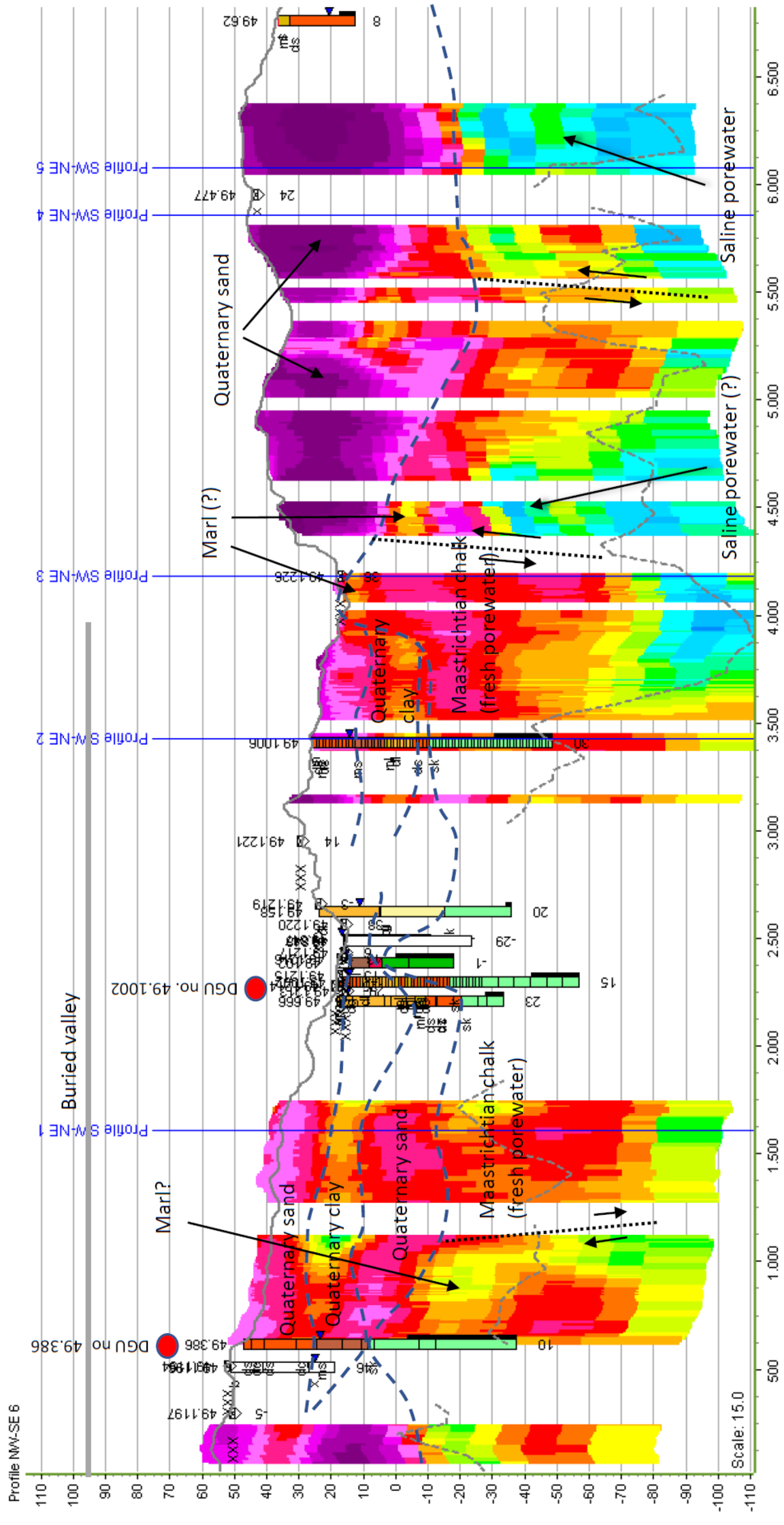

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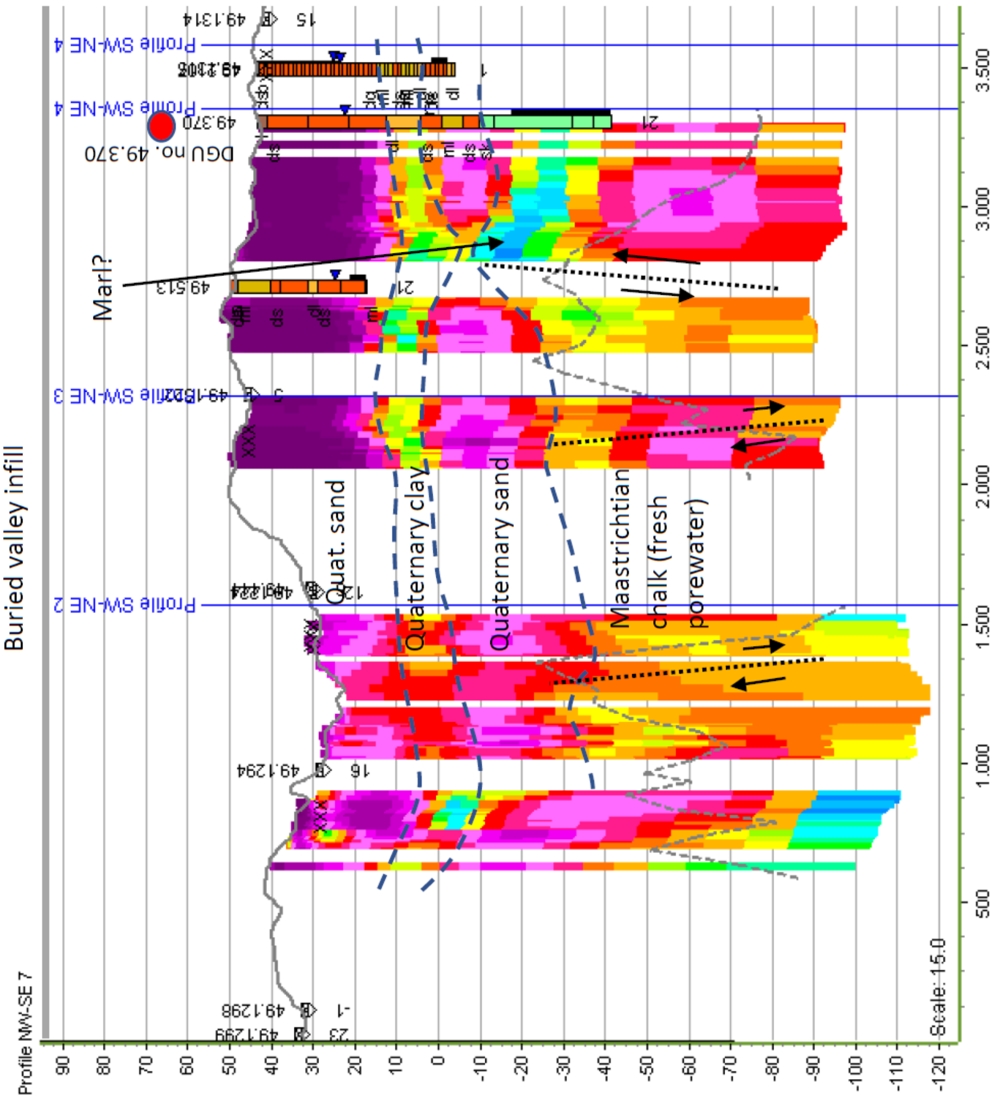

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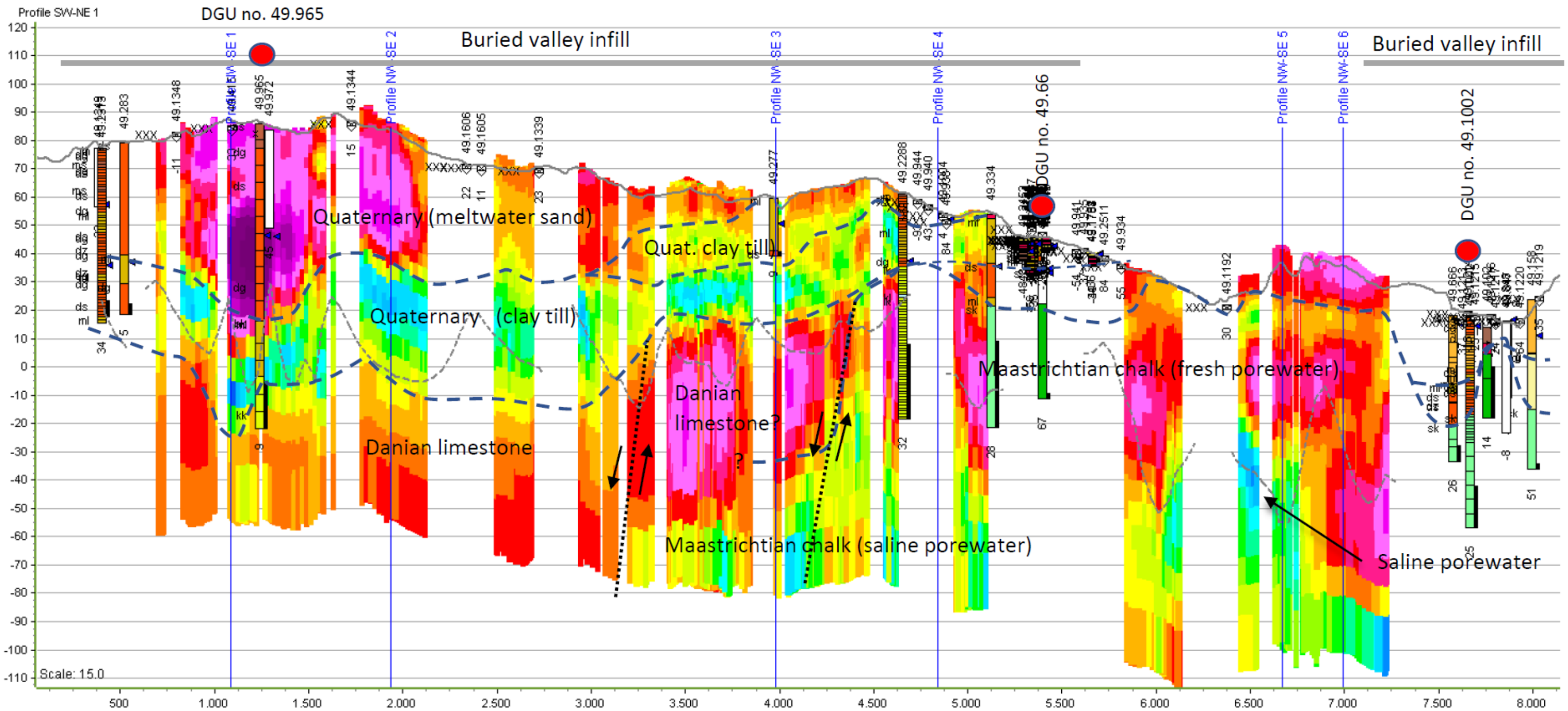

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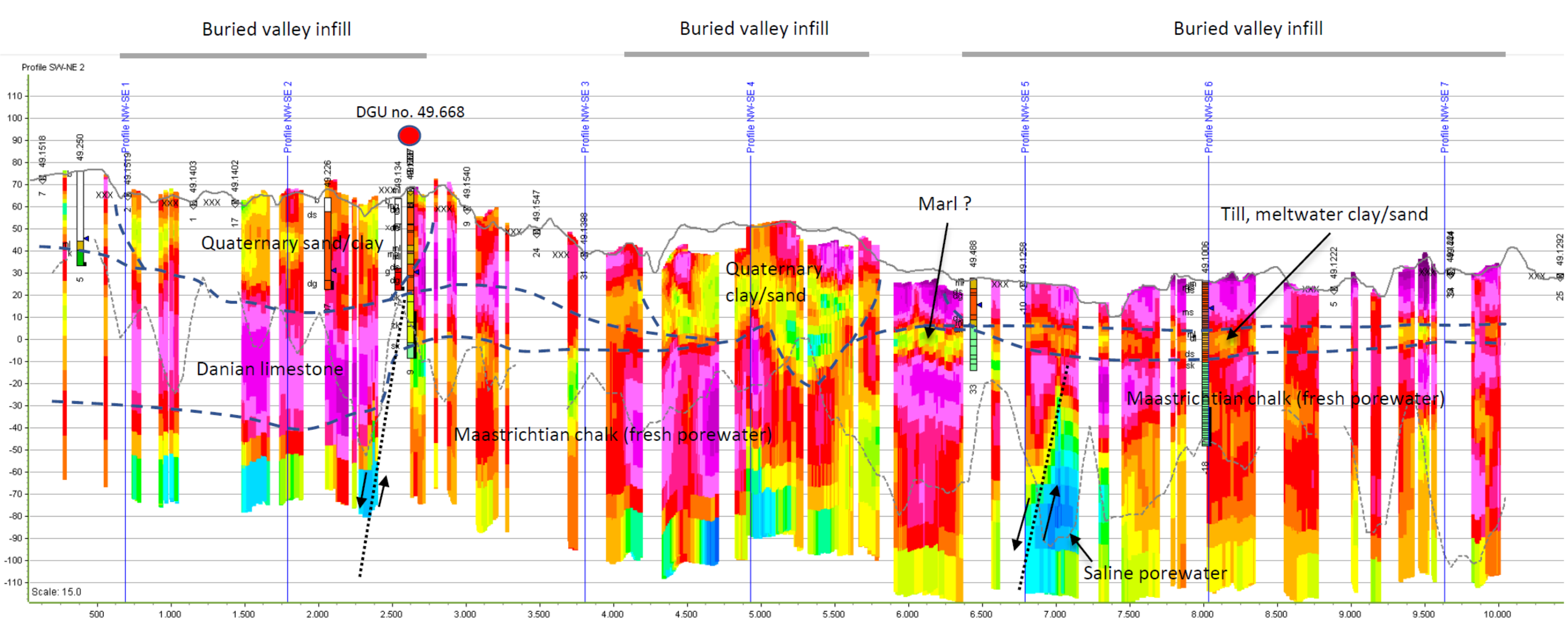

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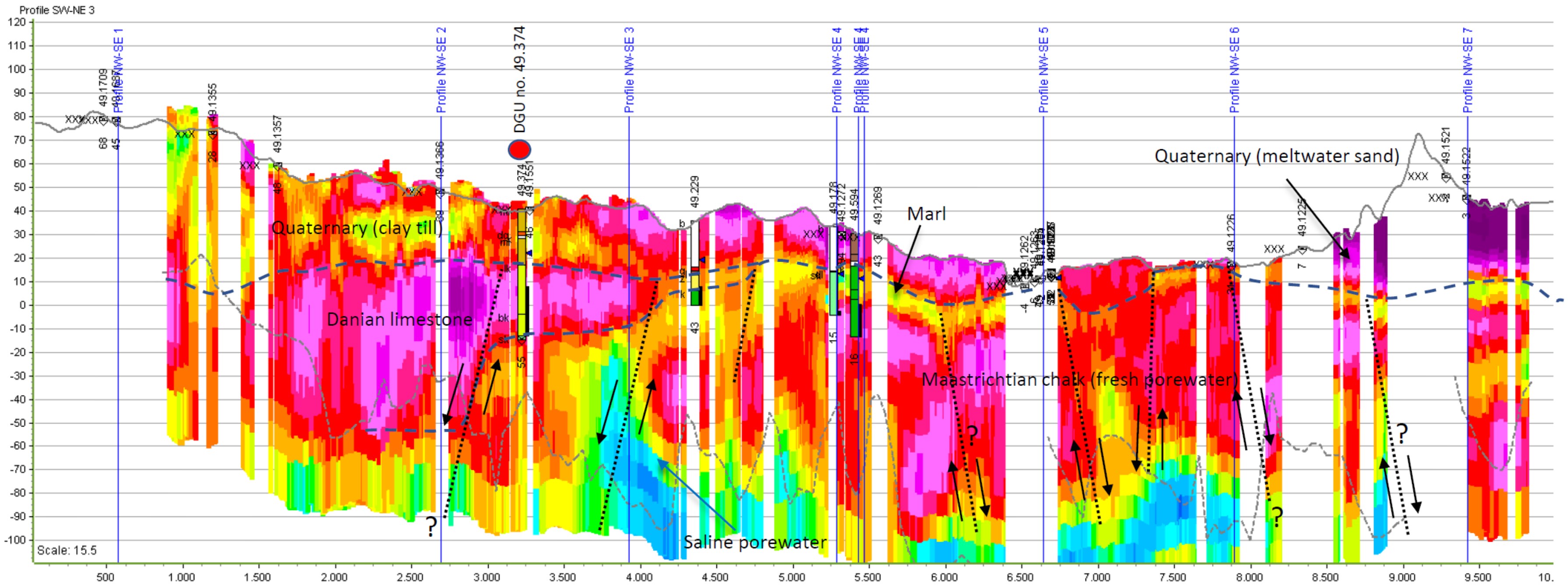

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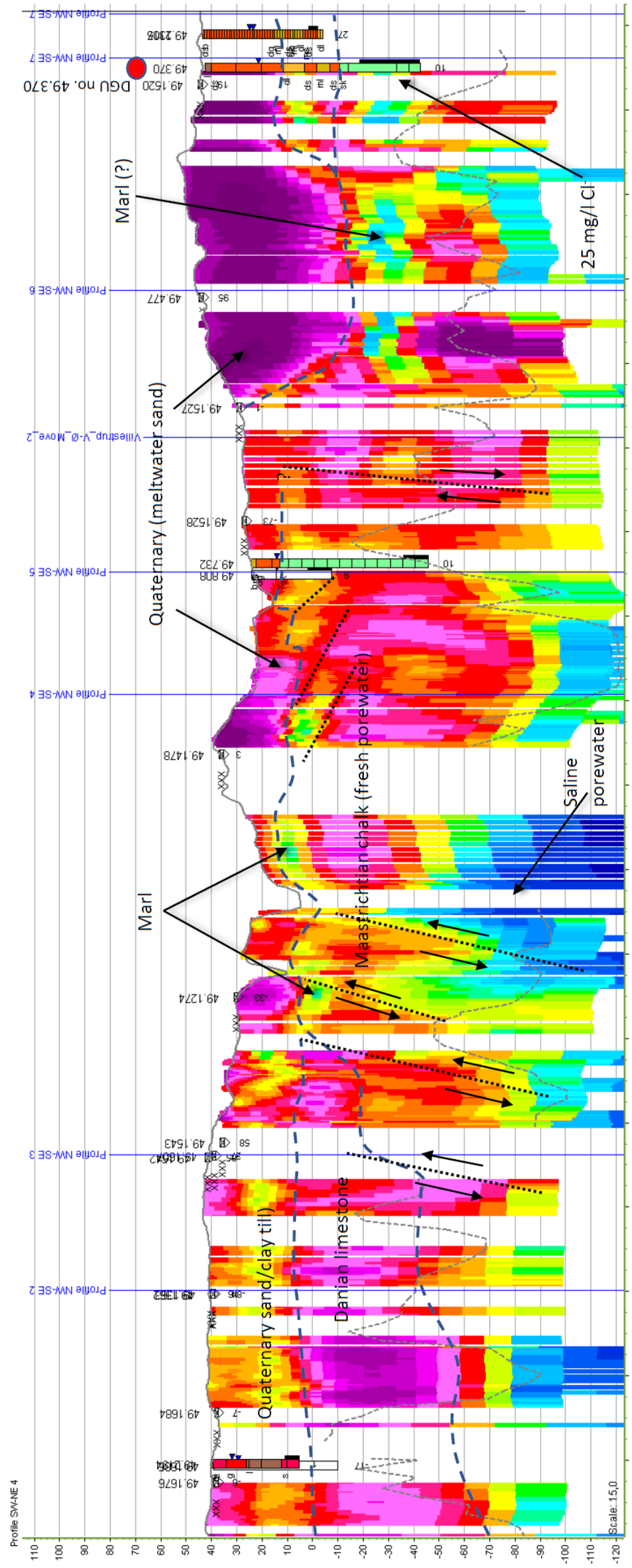

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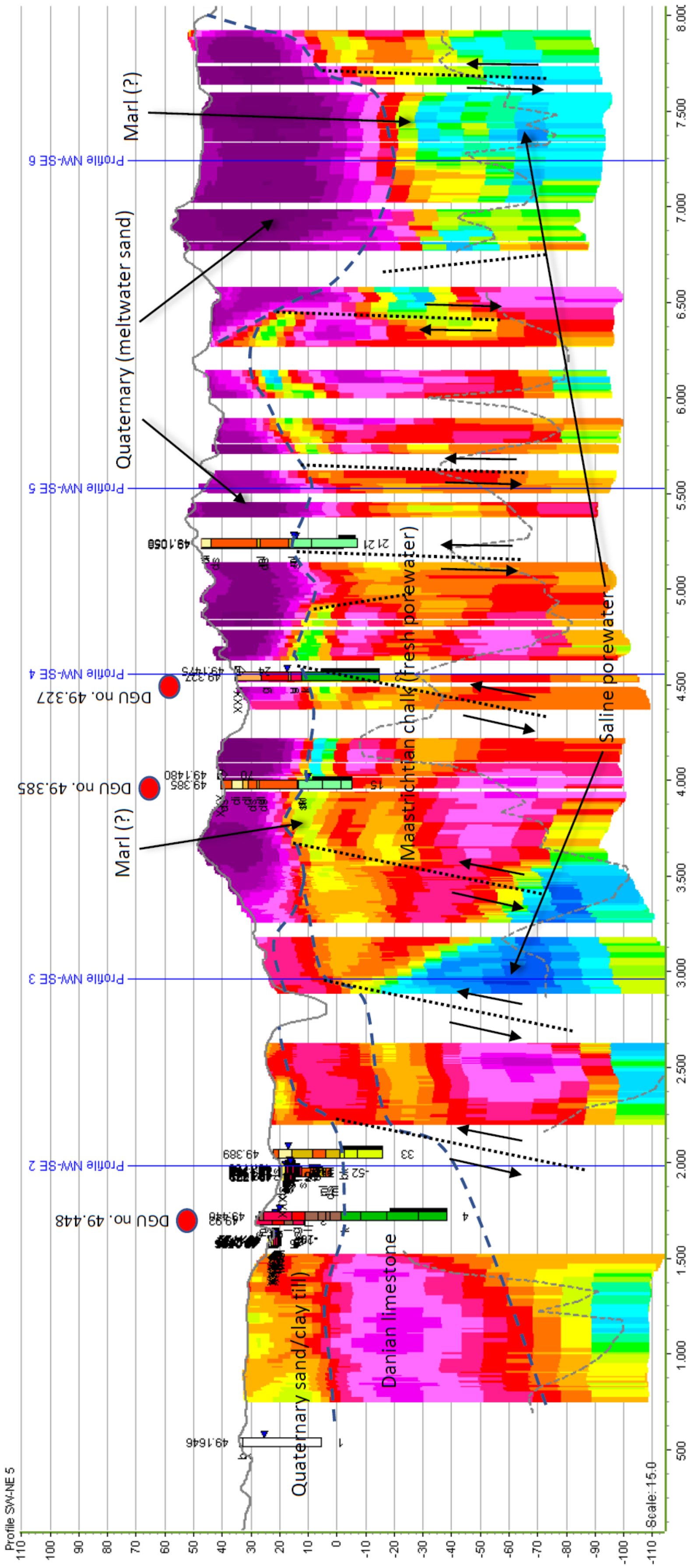

Profile NW-SE_move_1