*Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)*


# Regional geotechnical railway corridor mapping using airborne electromagnetics

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ABSTRACT: The Norwegian National Rail Administration (Jernbaneverket) is planning 230 km of railway construction and upgrades adapting for high speed trains to reduce commuting times to and from Norway's capital Oslo. Parts of the project are in areas with little or no prior geotechnical knowledge. To enable an efficient and economic ground investigation program, we conducted a high-resolution airborne electromagnetic mapping (AEM) campaign covering 600 km2 in summer 2015. The investigation area includes various types of geotechnical and geological challenges and the AEM data contribute to the detailed railway alignment design. Primary delivery is depth to bedrock varying from tens of meters glaciomarine clay to few meters moraine or coarse-grained sediments. Detailed analysis of the final AEM resistivity models leads to quick clay appraisal, alum shale detection and indications for major bedrock weakness zones. A tight integration of accurate geophysical models and sparse geotechnical data is a key element in this project.

## 1 INTRODUCTION

After decades with minor investments, linear infrastructure development has recently become a significant factor for the Norwegian geotechnical industry. Tens to hundreds of km with upgraded and new roads and railroads are currently being planned, designed and constructed. The typically demanding topography and geology requires extensive pre-investigations, which so far were carried out from the ground.

High-resolution time-domain AEM has been used previously in Norway for bedrock mapping with great success for both road and railway design projects. Christensen et al. (2015) present a geotechnical case study using AEM to assess bedrock depth for a planned highway section northeast of Oslo. It has been shown that in favorable cases AEM may even distinguish saline, marine clay from leached and potentially sensitive clay (Anschütz et al. 2016a). These results and experiences provided the basis for the large-scale survey discussed here:

A high resolution airborne electromagnetic (AEM) survey was carried out during 6 weeks in summer 2015, covering about 600 km2 extending over 9 separate geotechnical project areas. The AEM data were used to create a geomodel for the detailed railway alignment and design: the primary purpose was to obtain information of depth to bedrock in areas with little or no prior geotechnical knowledge. Bedrock topography is indeed the main target for geotechnical surveys in terms of stability and mass balance as well as for tunnel planning in terms of bedrock topography at portals and expected rock cover along the tunnel.

To illustrate the various aspects of the project we show three data examples that demonstrate the deliveries in terms of (a) bedrock topography in general in an area with good to moderate contrast, (b) indications for leached marine clay (quick clay) in a small area that is known to contain quick clay units and finally (c) a tunnel example where the data show lacking rock cover and a thrust zone crossing the tunnel alignment.

## 2 METHOD

The survey was flown with a SkyTEM304 system (Sørensen and Auken, 2004) with one turn in the low moment and a peak moment of 3000 Am$^2$ and four turns in the high moment with a peak moment of 150 000 Am$^2$. The resulting time gates range from < 10 µs to 2 ms. This bandwidth provides an excellent trade-off between high near surface depth resolution and moderate penetration depth. Nominal line spacing was 100 m throughout the entire area of investigation. Around 6000 line-km of AEM data were acquired within six weeks. Processing and inversion was done with the Aarhus Workbench spatially constrained inversion (SCI, Viezzoli et al. 2008) with moderately loose vertical and horizontal constraints and automatic starting models to account for the heterogeneous geology ranging from outcropping resistive bedrock to tens of meters with conductive, marine clay. Bedrock topography interpretation involved a combination of resistivity thresholds, vertical resistivity gradient, manual picking and sparse geotechnical boreholes (Anschütz et al. 2016b).

## 3 GEOLOGICAL BACKGROUND

The demanding topography and geology in Norway requires costly and long lasting pre-investigation phases for major geotechnical projects. The extent and thickness of marine clay and other glacial sediments as well as the occurrence of toxic black shale or bedrock weakness zones are factors that determine feasibility and construction costs and are all suitable targets for an AEM survey. Figure 1 gives typical examples of encountered quaternary sediments. Bedrock mostly comprises medium to highly metamorphic sedimentary and igneous rocks with a high abundance of gneiss, schist and phyllite. With the exception of highly conductive cambro-silurian black shales found around Oslo, the bedrock is highly resistive and makes a suitable AEM contrast to the conductive sediments. Tracking bedrock topography from AEM is feasible for large parts of the investigated lowlands. A minor part of the more than 6.000 km AEM data acquired in 2015 was not transferable to a bedrock model due to lacking resistivity contrast between bedrock and electrically resistive moraines or shallow surface weathering. In the highlands, above the marine limit and thus free of conductive marine sediments, bedrock topography tracking is limited to wetlands (bogs) that pose a good enough resistivity contrast for AEM.

## 4 RESULTS

The main task is to convert the 3D AEM resistivity models into bedrock topography. We have previously computed detailed bedrock models based on spatial correlation of the AEM data combined with sparse boreholes (Christensen et. al. 2015). For most of the data discussed here, we combine automatic and manual interpretation (Anschütz et. al. 2016b) largely based on the resistivity models and geological maps validated by boreholes at only a few locations (Figure 2).

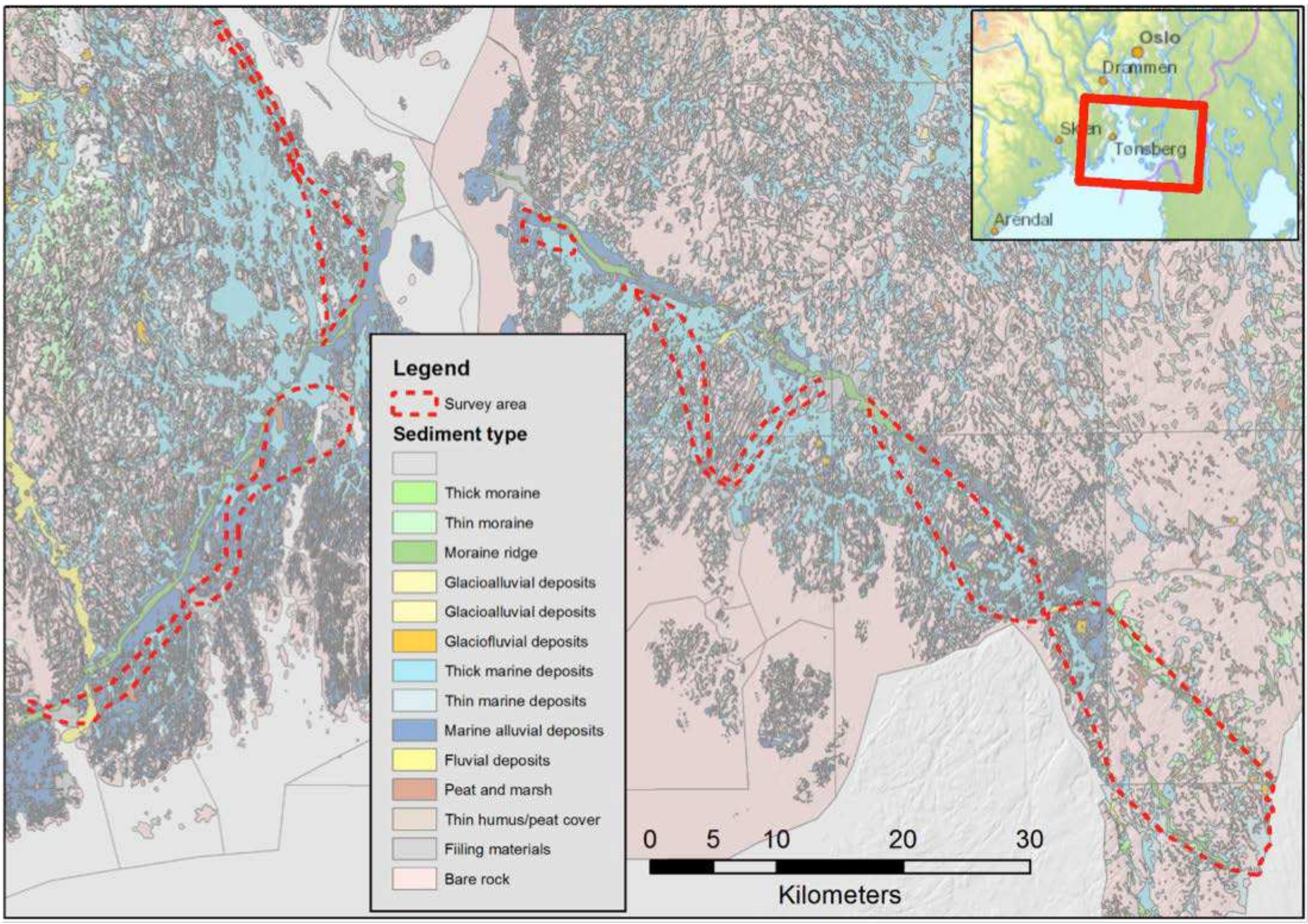
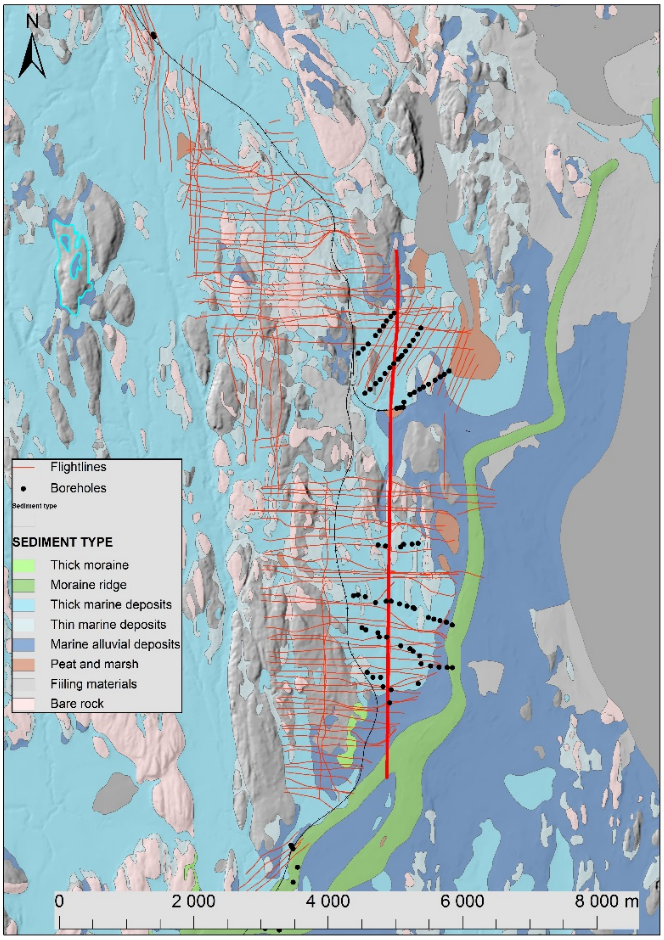
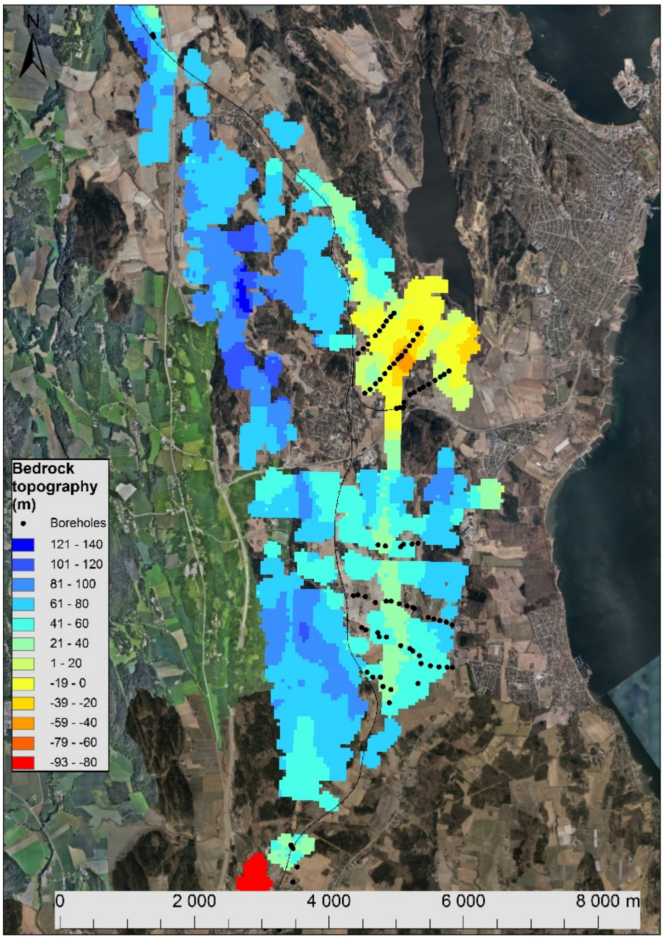



Figure 1. Quaternary geological map of the southern survey area covering five of the nine project areas. Approximate survey extent drawn for illustration, a grid of flight lines with 100 m spacing covers close to 600 km2 in total.



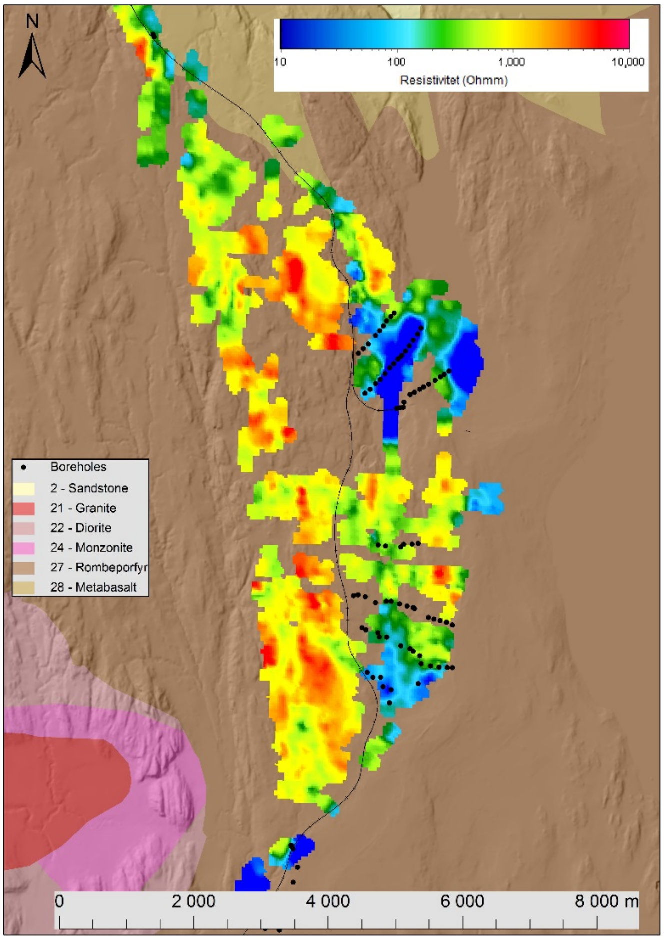




Figure 2a: Left: Quaternary geology map along with flight lines (red) and existing railway (thin black). Bottom: Bedrock types and resistivity depth slice with average resistivity from 15 to 30 m below ground with geological map outlining various volcanic units over shaded DEM. Right: Bedrock topography model derived from AEM data over an aerial image

To quantify uncertainty we pick a maximum and minimum bedrock elevation, subjectively chosen based on resistivity contrast, depth, distance to boreholes, consistency with a priori data, etc. Sediment thickness varied from meters to tens of meters and the bandwidth and signal to noise ration of the AEM data was sufficient to resolve sediment depths within the geotechnical relevant range. In some cases, we were able to interpret bedrock beneath up to 100 m of marine clay with resistivity lower than 10 Ωm, albeit with a higher uncertainty.

Further to bedrock delineation, characterizing the sediment type is of additional value. Norway is prone to so-called quick clay, highly sensitive formerly marine clay that liquefies at failure and poses a serious geohazard. Electrical resistivity is a valuable factor when it comes to distinguishing unleached (stable) and leached (sensitive) clay (Rømoen et al. 2010). The resistivity contrasts are subtle and consequently only accurate and high resolution resistivity models can provide the desired information.

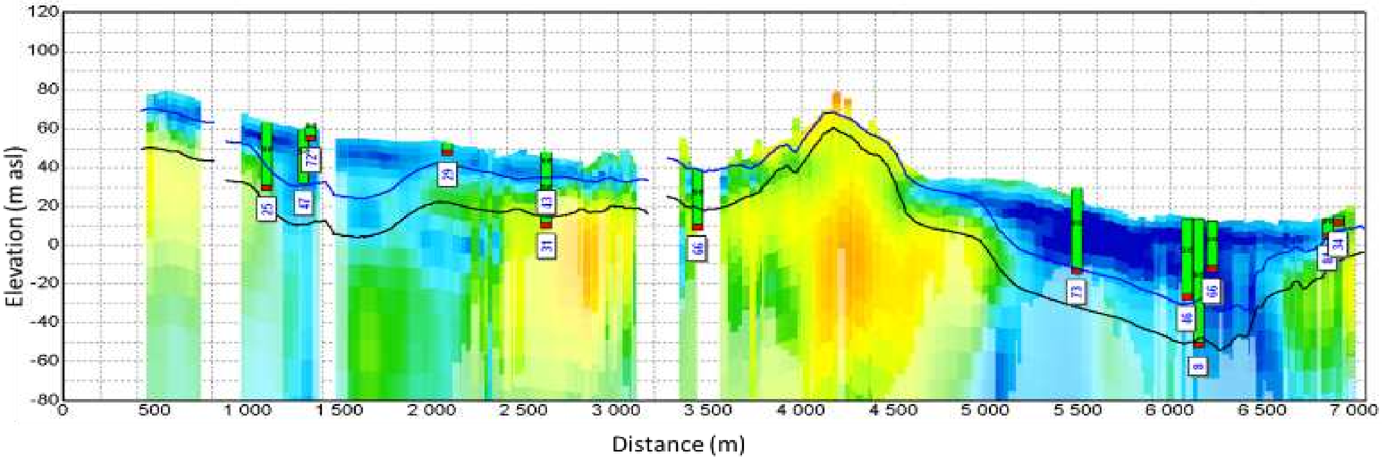



Figure 2b: Resistivity model (same resistivity colour scale as on map) from S-N along one of the very few profiles with boreholes close to the AEM data (thick red line in left map). Off-line distance of boreholes denoted in meters below the bars, the bars extend until assumed bedrock. The blue and black lines illustrate the lowest and highest assumed bedrock.

Previous field trials (Anschütz et. al. 2016a) have shown that this criteri-on is met for our data and we thus use the acquired resistivity models as indications of clay salinity and consequently probability for quick clay, provided the sediment layer is thick enough. The profile in Figure 3 clearly shows a valley filled with some tens of meters marine clay with some tens of Ωm resistivity, typical for leached marine clay. Geotechnical drillings confirmed the assumption and found sensitive quick clay. We are currently extending our interpretation to quick clay probability maps, based on a spatial search for sediments with resistivity typical for quick clay.

The results discussed so far focus on geotechnical issues such as depth to bedrock and sediment properties (indications for leached clay). For near surface AEM systems the depth of investigations typically extends to some hundred meters depending on the geology. We utilize this deeper part of the data in areas that will be crossed with tunnels. Geophysical targets are major weakness zones and/or existence of black shale due to their impact on tunnel

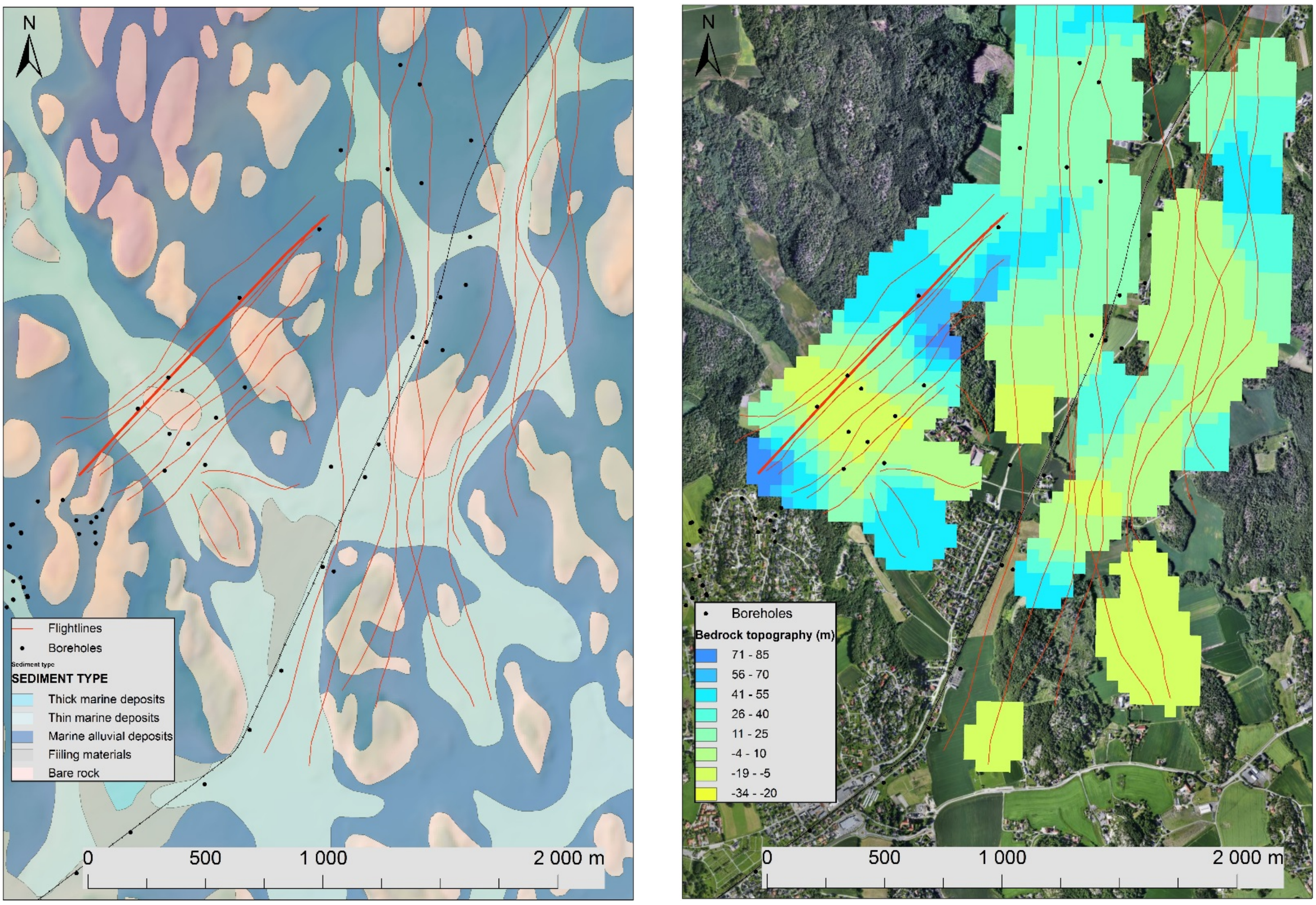



Figure 3a: Left: Quaternary geology map along with flight lines (red) and existing railway (black). Right: Bedrock topography model derived from AEM data over an aerial image.

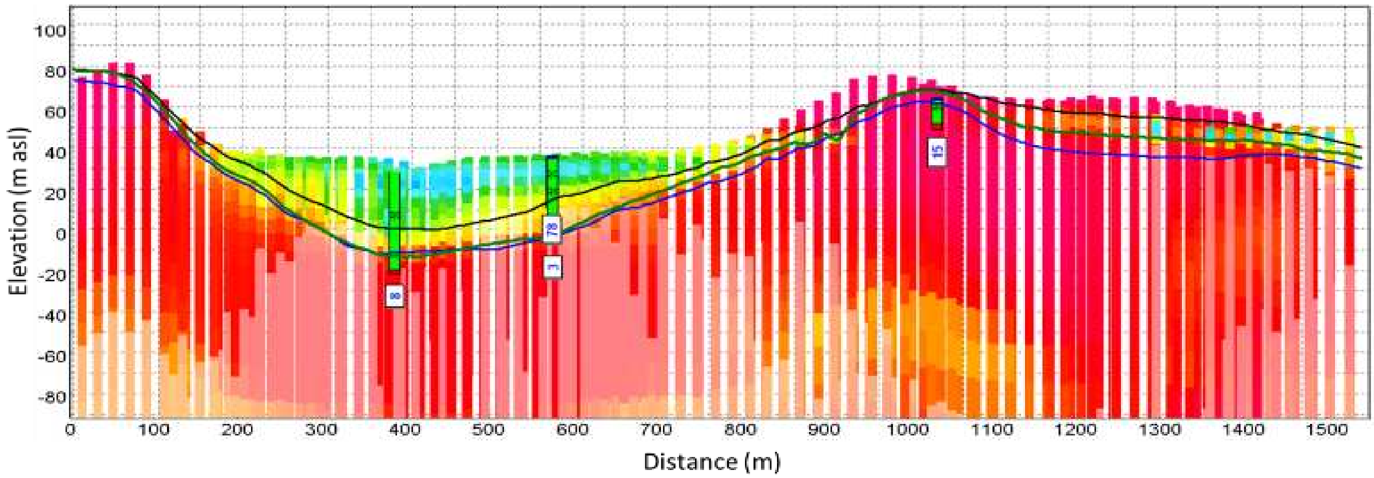


Figure 3b: Resistivity model (same resistivity colour scale as on map) from SW-NE along the profile drawn on the left map. The green line shows an adjusted bedrock model, based on the boreholes. The resistivity models result from a constrained inversion based on the green bedrock interface. Note the subtle variation in clay resistivity from below to above 10 Ωm indicating leached marine clay and thus a chance for sensitive quick clay.

construction costs. In areas prone to the occurrence of uranium rich black shales the models outline highly con-ductive structures (resistivity around and below 1 Ωm) that can consequently be avoided if possible (not shown). The final data example (Figure 4) shows a potential tunnel alignment that was finally considered as not feasible due to lack of rock cover in the western part. The model also shows a strong electrical conductor crossing the alignment, a thrust zone where phyllite has been reworked to clay. It is worth mentioning that this zone most probably isn't as thick as it appears in the resistivity section due to decreasing resolution with depth; The zone may rather be meters, than tens of meters thick. Note that not all areas with low near surface resistivity are due to sedimentary cover. In the eastern part of the survey, low resistivity indicates outcropping thrust zones rather than marine sediments.

The high efficiency, beneficial economics, survey robustness and data accuracy of modern AEM makes it a strong candidate for early phase investigations both in terms of geotechnical design (e.g. bedrock topography and stability) and engineering geology (e.g. major weakness zones). Based on our experience, the AEM vertical resistivity resolution is very close to ground measurements (ERT) with the exception of the very first meters.

Processing, inversion and interpretation is the crucial element of AEM investigations as for any other geophysical data. Without a geophysical contrast, no parameter such as bedrock topography can be derived though (resistive cover over resistive bedrock). A remaining challenge is to quantify depth uncertainty: transferring data standard deviation and inversion sensitivity to a bedrock model uncertainty in meters is neither state of practice nor firmly established in academia.

## 5 CONCLUSIONS

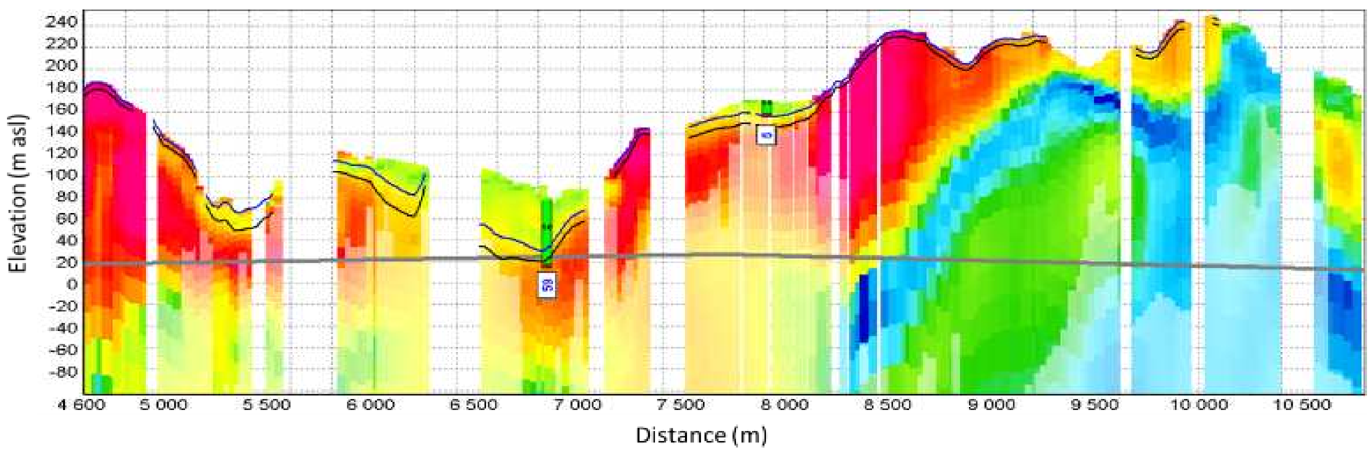
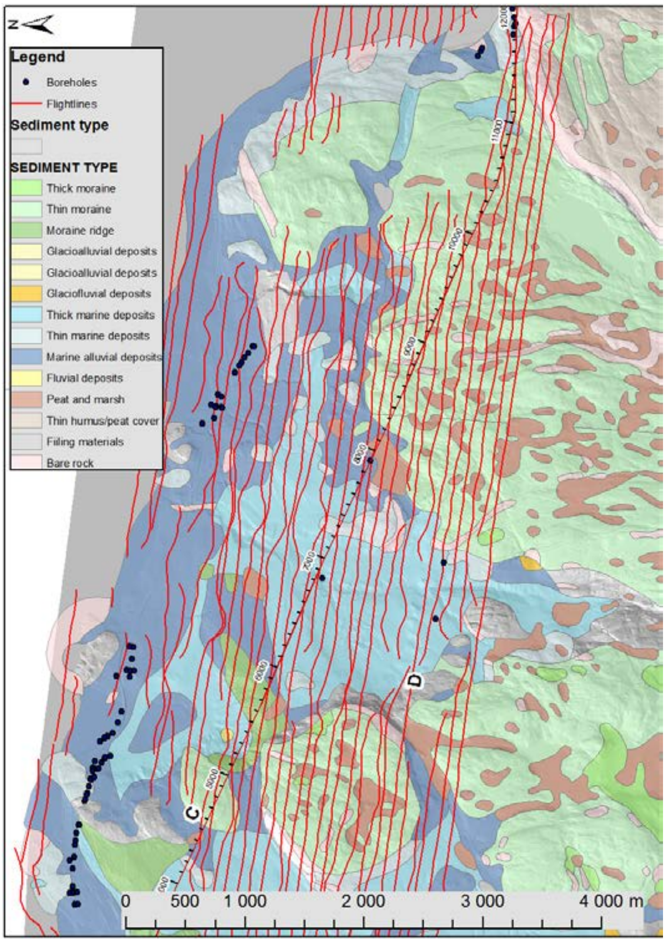
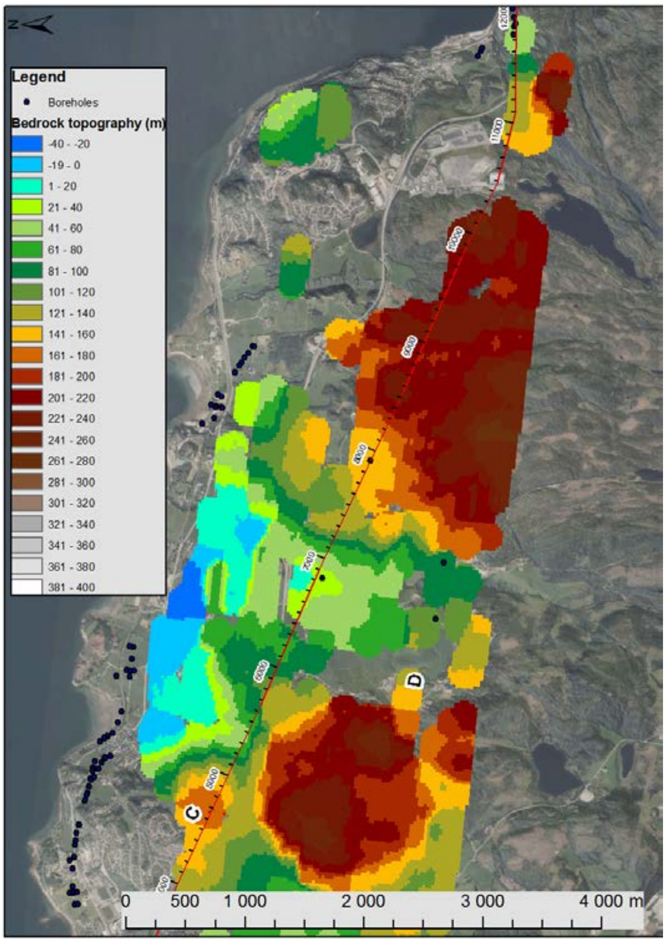


Figure 4a: Resistivity model (same resistivity color scale as on map) from SW-NE along the profile drawn on the map. The grey line sketches a potential tunnel alignment that would encounter a lack of rock cover at profile coordinate 6 500 – 7 000 m and crosses a low resistivity zone at 8 500 m as well as further east.



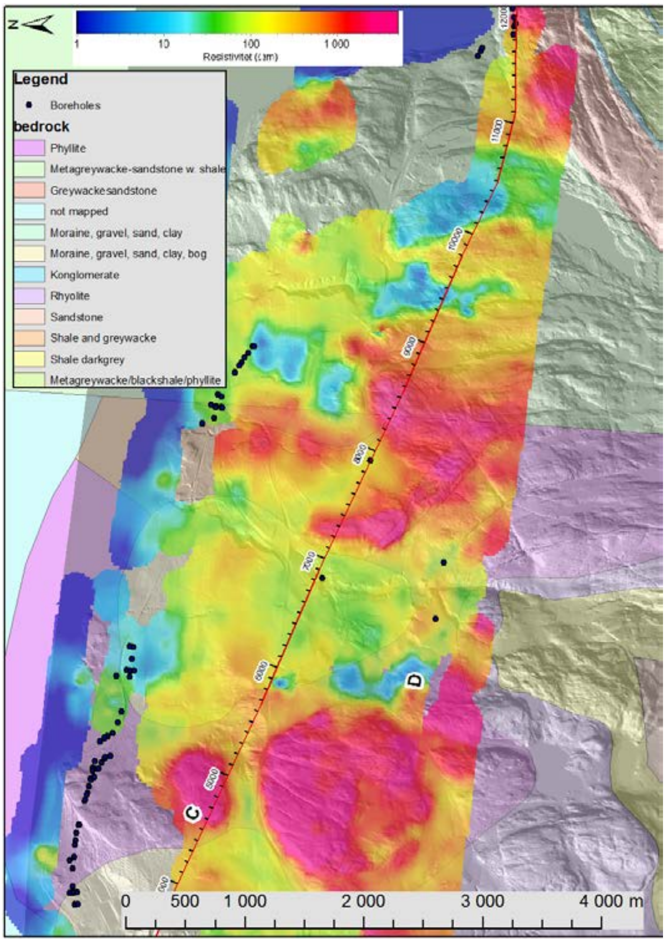




Figure 4b: Survey maps as in Figure 2 with one exception: Resistivity depth slice from 10 to 20 m below ground.

## 6 ACKNOWLEDGMENTS

The Norwegian National Rail Administration, the owner of all shown results, gave permission to publish these data,

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